UNIVERSIDAD
DE GRANADA

# TESIS DOCTORAL

## ESTUDIO DE LAS PROPIEDADES MECÁNICAS DE MATERIALES ASFÁLTICOS EN SERVICIO PARA LA OPTIMIZACIÓN DE LAS SOLUCIONES DE CONSERVACIÓN DE FIRMES DE CARRETERAS

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PROGRAMA DE DOCTORADO: INGENIERÍA CIVIL (B23.56.1)
LÍNEA DE INVESTIGACIÓN: INGENIERÍA DE LA CONSTRUCCIÓN Y DEL TERRENO

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Febrero de 2023

Editor: Universidad de Granada. Tesis Doctorales
Autor: Francisco Javier Sierra Carrilo de Albornoz
ISBN: 978-84-1117-804-4
URI: https://hdl.handle.net/10481/81252

# AGRADECIMIENTOS.

A Dios, porque, a pesar de las dudas, siempre acaba siendo Faro en mi vida.

A mis padres, porque gracias a su ejemplo y entrega se cimentaron los pilares que me han formado como persona, y sin los que nada de esto hubiera sido posible.

A Olga, mi mujer, por acompañarme siempre, sin esperar nada a cambio. Porque sobre esos cimientos has levantado una maravillosa estructura, siempre firme, en la que me guías y me mejoras día tras día.

A mis hijos, Javier, Saleta y Olga, por haberlo cambiado todo, llenando esta extraordinaria familia que da sentido pleno a mi vida.

A mi hermana Saleta, por estar siempre ahí recordándome que la bondad existe en el corazón de las personas, siendo el mejor ejemplo de ello.

A mi hermano Luis, por haberme encauzado como Ingeniero de Caminos, Canales y Puertos, siendo el mejor modelo y referente posible de esta profesión que adoro.

A la Consejería de Fomento de la Junta de Andalucía, por poner a disposición su Red de Carreteras para esta investigación, sin la que hubiera sido imposible hacer esta tesis doctoral.

A mis compañeros del Servicio de Carreteras de Granada, donde he crecido como funcionario, como ingeniero y como persona. Por haberme acompañado estos últimos 12 años dándome tanto afecto que difícilmente podré devolver.

A las empresas Construcciones Pérez Jiménez y OPR, por haber abierto su casa a la investigación, al desarrollo y a la innovación, convirtiéndose en referentes como empresas asfalteras.

Al Laboratorio de Ingeniería de la Construcción de la Universidad de Granada, por haberme adoptado como a un miembro más de la familia. Especialmente al Dr. Miguel Sol, la Dra. Gema García y el Dr. Raúl Tauste. Vuestra sencillez ha convertido lo complejo en asequible.

A mi Profesora y Directora de Tesis, la Dra. M.ª del Carmen Rubio, por haber apostado por mí llevándome nuevamente a mi querida Escuela de Caminos de Granada. Has abierto mi mente a un nuevo mundo escoltándome en todo momento, orientándome y guiándome como la mejor Maestra. Nunca podré agradecerte suficientemente lo generosa que has sido conmigo.

Al Dr. Fernando Moreno, también Director de esta Tesis, por darme el mejor regalo: tu amistad. Eres un ejemplo con mayúsculas de dedicación y esfuerzo unido a un excelso talento intelectual. Talento que se enaltece si cabe aún más en lo personal, siendo una fuente inagotable de magisterio en todos los sentidos. Estos últimos seis años han sido un viaje apasionante que te agradeceré siempre.

# RESUMEN.

El comportamiento mecánico de las mezclas bituminosas está notablemente influenciado por las cargas del tráfico, la temperatura de servicio, el betún utilizado en su fabricación y su envejecimiento. De ahí la necesidad del análisis de la evolución de las propiedades mecánicas de diferentes tipos de mezclas bituminosas expuestas a distintas condiciones climatológicas y a diferentes cargas de tráfico, evaluando así el efecto combinado que estas variables, junto con el envejecimiento, pueden tener en su respuesta mecánica a largo plazo bajo condiciones de servicio reales. Este análisis permitirá diseñar mezclas bituminosas con mejores prestaciones mecánicas y por tanto más duraderas, optimizando el presupuesto de las administraciones para la conservación de pavimentos de carreteras. Esta optimización también debe focalizarse tanto sobre los recursos naturales, reciclando, reutilizando y valorizando residuos como componentes de las mezclas, como sobre las técnicas de fabricación, favoreciendo su sostenibilidad medioambiental, reduciéndose las emisiones de gases de efecto invernadero y el consumo de combustibles fósiles.

Por sus ventajas medioambientales, la utilización de betunes modificados con polvo de caucho obtenido de neumáticos al final de su vida útil (PNFVU) para fabricar hormigones bituminosos es una alternativa viable. Sin embargo, en la práctica, se emplean con menos frecuencia que los betunes modificados con polímeros convencionales, fundamentalmente por el escaso seguimiento de las experiencias ya realizadas. Por ello, esta investigación tiene como objetivo aportar información sobre la evolución del comportamiento de estos materiales, para lo que se seleccionaron unos tramos de autovía, todos ellos con condiciones climáticas severas y de tráfico elevado, donde la capa de rodadura estuviera compuesta por mezclas asfálticas diseñadas con betunes modificados con PNFVU. Asimismo, también se eligieron otros tramos contiguos a los anteriores, pero ejecutados con el tradicional betún modificado con el polímero SBS, con el objeto de comparar ambos materiales (tanto a nivel de ligante como de mezcla). Para ello, se extrajeron testigos en diferentes periodos de su vida útil.

En cuanto a los ligantes, se estudió el envejecimiento real de los betunes asfálticos modificados con PNFVU cuando se exponen a diversos factores, incluidos los gradientes de temperatura, la presencia de agua y la oxidación, bajo condiciones reales de climatología y de tráfico. Los ligantes de los testigos extraídos de las capas de rodadura fueron recuperados y ensayados usando el DSR (Dynamic Shear Rheometer) para determinar la evolución de los parámetros reológicos. El análisis del módulo complejo y el ángulo de fase se realizó mediante ensayos de barrido de frecuencia y temperatura, mientras que la evolución de la recuperación elástica, Jnr, L-Index y T-Index, se evaluaron mediante el ensayo MSCRT (Multiple Stress Creep and Recovery Test). Los resultados obtenidos indicaron que los betunes modificados con PNFVU muestran parámetros reológicos y de envejecimiento similares a los de los betunes modificados con polímeros convencionales, incluso en condiciones climáticas y de tráfico severas.

A nivel de mezclas bituminosas, se evaluó el comportamiento de las fabricadas con betunes modificados con PNFVU y con polímero SBS respectivamente, analizando en el laboratorio la evolución de la densidad, rigidez y resistencia a la fatiga de la capa de rodadura. En base a los resultados obtenidos en los ensayos, se puede concluir que, en condiciones de servicio reales y con climas severos y elevado tráfico, las mezclas asfálticas fabricadas con betunes modificados con PNFVU ofrecen prestaciones mecánicas y de envejecimiento muy similares a las que ofrecen las mezclas asfálticas fabricadas con betunes modificados con polímeros tradicionales como el polímero SBS, siendo por tanto una alternativa que ayudaría a minimizar los problemas ambientales causados por los vertederos de neumáticos.

Tras haber demostrado la viabilidad de uso del PNFVU como solución sostenible para obtener mezclas bituminosas duraderas y más eficientes a la hora de definir una solución óptima de conservación de firmes, se decidió encarar las principales limitaciones en su aplicación real, que son las altas temperaturas de fabricación y su baja trabajabilidad. De esta forma, se abordó la evaluación de una mezcla de capa de rodadura que combinara la reducción de temperatura (con la consiguiente reducción de emisiones de gases de efecto invernadero), con la valorización de PNFVU, testada bajo condiciones de puesta en obra, y en carreteras que soportan altos volúmenes de tráfico y condiciones ambientales severas. Para ello se realizaron diversos estudios tanto en laboratorio como en planta asfáltica (a nivel de ligante y de mezcla). Posteriormente, estos materiales sirvieron para construir un tramo de prueba en una autovía en un puerto de montaña (a 1400 m sobre el nivel del mar) soportando más de 3000 vehículos pesados cada día en condiciones ambientales severas (nieve en invierno y altas temperaturas y muchas horas de radiación solar durante el verano). Los resultados indicaron la viabilidad de utilizar estos materiales ya que, además de sus ventajas ambientales, proporcionan otra serie de ventajas como mejor trabajabilidad a bajas temperaturas y un incremento de su resistencia mecánica frente a las principales causas de agotamiento de los pavimentos asfálticos.

# ABSTRACT.

The mechanical performance of asphalt mixtures is notably influenced by traffic loads, service temperature, the binders used in its manufacturing and its ageing. That is why there exists the need to analyze the evolution of the mechanical properties of different kinds of asphalt mixtures exposed to distinct climate conditions and traffic loads, while assessing the combined effect that these variables, along with the ageing, could have in its mechanical response in the long-term under real service conditions. This analysis will enable us to design more durable asphalt mixtures with better mechanical performance, optimizing government budgets for pavement maintenance. This optimisation has to be focused both on natural resources, recycling, reusing and valorizing waste products as mix componentes, and on manufacturing techniques, to stimulate their environmental sustainability, reducing the greenhouse gasses emissions and the fossil fuel consumption.

Due to their environmental advantages, the use of crumb rubber modified binders constitute a feasible alternative to produce asphalt mixtures. However, in practice, they remain less commonly used than conventional polymer modified binders, mainly due to the scarce tracking of the experiences already conducted. Thus, this research aims to provide information about the evolution of the mechanical performance of these materials. To this end, some highway sections where the surface layers were built with asphalt mixtures manufactured with crumb-rubber-modified bitumen with severe climatic and traffic conditions were selected. In addition, other sections built side by side the previous ones were chosen, but manufactured with the conventional SBS polymer modified bitumen, to compare both materials (at binder and mixture level). For this comparison, cores were taken at different periods of their service life.

Regarding binders, the real ageing of crumb rubber modified asphalt bitumens when exposed to various factors, including temperature gradients, the presence of water and oxidation, was studied under real traffic and climate conditions. The binders from cores of highway surface layers were recovered and tested using the DSR (Dynamic Shear Rheometer) to determine the evolution of the rheological parameters. The analysis of the complex modulus and phase angle was conducted based on frequency and temperature sweep tests, while the evolution of the elastic recovery, Jnr, L-Index and T-Index were assessed from the MSCRT (Multiple Stress Creep and Recovery Test). The results obtained indicate that crumb rubber modified binders show similar ageing and rheological parameters to those of conventional polymer modified bitumen, even under severe traffic and climate conditions.

Regarding asphalt mixtures, the performance of mixtures manufactured with crumb-rubber-modified bitumen and conventional SBS polymer modified bitumen was assessed by analyzing the evolution of the density, stiffness and fatigue resistance of the surface layers. Based on the results obtained from these tests, we could conclude that under real severe traffic and climate conditions, asphalt mixtures manufactured with crumb-rubber-modified bitumen offer ageing and mechanical performance very similar to that offered by asphalt mixtures manufactured with traditional SBS-modified bitumen, being a choice to minimize environmental problems caused by end-of-life tires in landfills.

After having demonstrated the viability of using crumb rubber as a sustainable solution to obtain durable asphalt mixtures, and also to obtain more efficient asphalt mixtures when designing the best option for pavement maintenance, it was decided to assess the main limitations of its real applications, which are high manufacturing temperatures and low workability. Thereby, a surface layer mixture which combined the reduction in temperature (with a reduction in greenhouse gasses emissions) with the use of crumb rubber from end-of-life tires was assessed. It was tested at the laboratory and on roads subjected to a high volume of traffic and severe climate conditions. Different studies were developed both in the laboratory and in an asphalt plant (at binder and mixture level). Later, these materials were used to construct a trial section in a highway at a mountain pass (at more than 1400 m above sea level) supporting more than 3000 heavy vehicles each day under severe environmental conditions (snow during winter, and high temperatures and many hours of solar radiation during the summer). The results indicate the viability of using these materials, since they provide, not only environmental advantages, but also a number of advantages such as improved workability at lower temperatures and an increase in its mechanical resistance against the main sources of distress that affect asphalt pavements.

# ÍNDICE GENERAL.

# ÍNDICE DE TABLAS.

# ÍNDICE DE FIGURAS.

# GLOSARIO DE ACRÓNIMOS.

| | |
|---|---|
| CB | Continuous Blend |
| CRMB | Crumb Rubber Modified Bitumen |
| DSR | Dynamic Shear Rheometer |
| EVA | Etilen Vinil Acetato |
| HMA | Hot Mix Asphalt |
| IRI | International Roughness Index |
| ITSM | Indirect Tensile Stiffness Modulus |
| ITSR | Indirect Tensile Strength Ratio |
| MSCRT | Multiple Stress Creep and Recovery Test |
| PAV | Pressure Ageing Vessel |
| PMB | Polimer Modified Bitumen |
| PNFVU | Polvo de caucho obtenido de Neumáticos al Final de su Vida Útil |
| RAP | Reclaimed Asphalt Pavement |
| RTFOT | Rolling Thin Film Oven Test |
| SBS | Styrene Butadiene Styrene |
| SBSMB | Styrene Butadiene Styrene Modified Bitumen |
| TB | Terminal Blend |
| TSRST | Thermal Stress Restrained Specimen Test |
| UGR-FACT | Fatigue Asphalt Cracking Test |
| WMA | Warm Mix Asphalt |
| WTS | Wheel Tracking Slope |

# 1. INTRODUCCIÓN.

## 1.1. ANTECEDENTES.

Las mezclas bituminosas son materiales visco-elásticos cuya respuesta mecánica está altamente influenciada por las cargas del tráfico, por su temperatura de servicio [1], y por el betún utilizado en su fabricación [2].

A elevadas temperaturas, los materiales bituminosos se comportan dentro de un rango más viscoso, de manera que son más susceptibles a sufrir deformaciones no recuperables ante las cargas de tráfico [3, 4]. Por el contrario, cuando la temperatura de servicio es baja, los materiales bituminosos se comportan de manera más elástica, y por tanto tienen una mayor capacidad para soportar esas tensiones de tráfico sin deformarse permanentemente [5]. Estas deformaciones permanentes se encuentran limitadas, y una vez consumida la capacidad de deformar del material, la energía introducida en cada ciclo de carga se disipa mediante daño por fatiga, el cual se propaga mediante fractura molecular [6]. Debido a estas circunstancias, la temperatura de servicio va a jugar un papel fundamental en la resistencia a fatiga de los materiales bituminosos.

No obstante, es necesario resaltar que la movilidad molecular del betún no sólo depende de la temperatura a la que se encuentran, sino que también está influenciada por otras variables como su composición química [2]. Por ello, el envejecimiento de los materiales asfálticos también va a tener un cometido clave en su respuesta mecánica a largo plazo [7]. Este fenómeno (presente durante toda su vida de servicio), es debido principalmente a la exposición de estos materiales al oxígeno y a la radiación ultravioleta, y conlleva la pérdida de volátiles, endurecimiento por exudación y oxidación [8]. Estos procesos provocan una modificación de la relación asfaltenos/maltenos, induciendo un incremento en la viscosidad del ligante, el cual se vuelve más duro y frágil [9]. Por todo esto, el fenómeno de envejecimiento de los materiales asfálticos provoca un incremento en su rigidez y una reducción de la ductilidad de la mezcla que puede conllevar una pérdida de su resistencia a fatiga [10].

Los pavimentos asfálticos estarán expuestos a diferentes temperaturas (que variarán diaria y anualmente) durante su vida de servicio, y sufrirán diferentes grados de envejecimiento, que terminarán provocando cambios en su respuesta mecánica a largo plazo. Asimismo, dichas temperaturas y grados de envejecimiento variarán en función de la zona climática donde se encuentren. Por todo ello, se hace necesario el análisis de la evolución de las propiedades mecánicas de diferentes tipos de mezclas bituminosas expuestas a distintas condiciones climatológicas y a diferentes cargas de tráfico, evaluando así el efecto combinado que el tráfico, la temperatura de servicio y el envejecimiento pueden tener en su respuesta mecánica a largo plazo bajo condiciones de servicio reales.

Este análisis nos facilitará el conocimiento del estado de los pavimentos y su presumible evolución, lo que nos ayudará a la elaboración de los presupuestos de conservación de carreteras, cuya principal unidad de obra es la de los hormigones bituminosos, que alcanza valores medios del 60% del total de la inversión en proyectos de conservación. Estos presupuestos han sufrido un notable descenso, lo que ha provocado un acusado deterioro de los pavimentos, obteniendo una calificación en España en el año 2020 de deficiente, a escasos puntos de muy deficiente, lo que supone la peor nota desde el año 2000 [11]. Este deterioro ha continuado aumentando hasta 2022 [12]. Por todo ello, es de capital importancia que la durabilidad de los pavimentos que diseñemos y ejecutemos sea la máxima posible, de forma que pueda demorarse la renovación de las capas de rodadura, siempre que se mantengan condiciones de comodidad y seguridad para los usuarios. De esta forma, se conseguirán optimizar los escasos recursos económicos disponibles. Para conseguirlo habrá que diseñar mezclas bituminosas con cada vez mejores prestaciones mecánicas y por tanto, más duraderas, para lo que el betún utilizado en la fabricación tendrá una gran influencia.

Pero esta optimización también debe afectar a los recursos naturales. Deben utilizarse productos y técnicas enfocados a la economía circular. En cuanto a los productos, debe tenderse al reciclaje, la reutilización y la valorización de residuos evitando la sobreexplotación de recursos naturales. Y en cuanto a las técnicas, deben ser más sostenibles medioambientalmente, reduciendo las emisiones de gases de efecto invernadero y el consumo de combustibles fósiles.

En relación con las técnicas de fabricación, se deben desarrollar procesos constructivos más sostenibles para minimizar el consumo de materias primas y energía, al tiempo que se reduce la contaminación que se genera durante las actividades de construcción, mantenimiento o rehabilitación. Por lo tanto, uno de los desafíos actuales en la industria de pavimentación de carreteras concierne a la implementación de una economía circular en la que se apliquen técnicas de construcción más respetuosas con el medio ambiente [13-15].

Dados estos desafíos actuales, el uso del polvo de caucho obtenido de neumáticos al final de su vida útil como modificador del ligante se está convirtiendo en una solución cada vez más extendida debido a los beneficios ambientales por reducir la acumulación de este residuo, junto con el hecho de que este modificador parece proporcionar al ligante una mayor viscosidad que los polímeros convencionales (como SBS y EVA) [16]. Esto permite el uso de dosis más altas de betún durante la fabricación de mezclas asfálticas, lo que a su vez da como resultado una mayor resistencia a la rotura [17, 18], al tiempo que reduce las deformaciones permanentes, el envejecimiento del ligante y la susceptibilidad a las fluctuaciones de la temperatura de servicio [19, 20].

Los neumáticos al final de su vida útil son uno de los tipos de residuos sólidos más producidos en todo el mundo [21]. Están compuestos por materiales de alta calidad tales como caucho, fibras metálicas, fibra de nailon, etc., que son difícilmente degradables pero que pueden presentarse como alternativas interesantes de materias primas cuando se reutilizan para un segundo uso. Por lo tanto, durante las últimas décadas se han realizado muchos esfuerzos para encontrar aplicaciones para la valorización de los neumáticos al final de su vida útil [22-26].

Una de las aplicaciones más comunes y exitosas, como se ha comentado anteriormente, es la reutilización de su caucho como modificador de ligante en mezclas bituminosas. Para ello, el caucho del neumático se transforma en polvo y se incorpora al ligante asfáltico (vía húmeda) o directamente a la mezcla como parte del esqueleto mineral (vía seca) [27]. Ese polvo de caucho obtenido de neumáticos al final de su vida útil (PNFVU) ha sido utilizado como modificador de materiales bituminosos en todo el mundo durante décadas [27]. Este modificador mejora el comportamiento mecánico de los materiales asfálticos incrementando su resistencia a la rotura por fatiga y a las deformaciones plásticas, y reduce su envejecimiento y el ruido de rodadura [28-33]. A su vez, esto da como resultado capas de rodadura de mayor durabilidad con menor necesidad de mantenimiento. Los distintos países, incluido EE.UU., tienen una amplia experiencia con el uso de mezclas asfálticas modificadas con PNFVU en todo tipo de carreteras y climas, y han demostrado las ventajas antes mencionadas sobre su aplicación [34-39].

Además de las ventajas técnicas que ofrece el PNFVU en materiales asfálticos, también ofrece una gran oportunidad para reducir el impacto ambiental causado por la construcción y rehabilitación de carreteras [40-42]. La incorporación de PNFVU en materiales asfálticos permite la valorización de un residuo que la mayoría de los países generan en grandes cantidades [43]. A su vez, se alinea con los principios de una economía circular y, por tanto, contribuye a los objetivos globales de desarrollo sostenible y a la gestión más eficaz de los recursos naturales, económicos y energéticos. Su aplicación como modificador en mezclas bituminosas permite la valorización de este residuo en grandes cuantías, (se podrían reutilizar unos 1000 neumáticos por kilómetro de carretera, al utilizar una mezcla bituminosa modificada con un 0,5% de su peso total y una capa de espesor de 6 cm).

Sin embargo, a pesar de todas estas ventajas ambientales y técnicas, la aplicación del betún modificado con PNFVU (CRMB) en España sigue siendo limitada, especialmente en capas de rodadura y carreteras de elevado volumen de tráfico o en condiciones climáticas severas [44, 45]. Una de las principales razones de ello radica en la falta de información y seguimiento de las experiencias ya realizadas. El comportamiento mecánico de estas aplicaciones no ha sido debidamente documentado y hay falta de información, lo que impide que los administradores de carreteras seleccionen estos materiales en lugar de los tradicionales ligantes modificados con estireno-butadieno-estireno (SBSMB), que tienen un empleo fiable y décadas de éxito.

Todo ello justifica la necesidad de investigar sobre las propiedades mecánicas de estos materiales asfálticos en función de la carga de tráfico y la climatología, con la finalidad de ofrecer soluciones óptimas para conservación de firmes de carreteras, objeto de esta tesis doctoral.

## 1.2. CONTENIDO Y ALCANCE DE LA INVESTIGACIÓN.

Para alcanzar el objetivo propuesto, esta tesis doctoral se ha conformado mediante el siguiente compendio de publicaciones:

1. *Ageing of Crumb Rubber Modified Bituminous Binders under Real Service Conditions*, en la revista SUSTAINABILITY.

2. *Analysis of the Real Performance of Crumb-Rubber-Modified Asphalt Mixtures*, en la revista MATERIALS.

3. *High-Performance Sustainable Asphalt Mixtures for High-Volume Traffic Roads in Severe Climates*, en la revista SUSTAINABILITY.

El primer artículo analiza el comportamiento de los betunes modificados con PNFVU. Para aumentar la confianza en ellos y al mismo tiempo apoyar el desarrollo sostenible y la economía circular, debe realizarse un análisis en profundidad de las propiedades reológicas del betún modificado con PNFVU en condiciones reales de tráfico y clima. Para lograr este objetivo, se llevó a cabo una investigación cuyo objetivo principal fue estudiar la evolución de las prestaciones mecánicas de estos materiales durante su vida útil en comparación con el tradicional betún modificado con polímero SBS. Para ello, se extrajeron CRMB y SBSMB de testigos obtenidos directamente de las capas de rodadura de dos autovías andaluzas en fechas diferentes. Posteriormente, los ligantes fueron ensayados en laboratorio mediante diversos ensayos reológicos (barridos de frecuencia y temperatura y MSCRT (Multiple Stress Creep and Recovery Test), utilizando el DSR (Dynamic Shear Rheometer)) para determinar la evolución de sus propiedades mecánicas durante su vida útil. Estas carreteras están sujetas a algunas de las condiciones más desfavorables de Andalucía en términos de clima y tráfico. En esta tesis se resumen, entre otros, los principales resultados obtenidos para los betunes a partir de este trabajo de investigación.

Posteriormente, en el segundo artículo se procede al estudio de las mezclas bituminosas fabricadas con betún modificado con PNFVU. Tras décadas de uso, son muchas las experiencias que ya han demostrado las ventajas de la aplicación del PNFVU como modificador de las mismas [34-42]. Sin embargo, en otros países, como España [44, 45], existen dudas sobre su eficacia a largo plazo, al igual que con los betunes. Por lo tanto, la aplicación del polvo de caucho no es común. Además, existe cierto escepticismo sobre su trabajabilidad en climas fríos [46], su estabilidad para formar una mezcla homogénea [47] o su resistencia al deslizamiento [48], así como sobre su viabilidad económica y ambiental [49].

Con el objetivo de conocer en profundidad el comportamiento real de las mezclas bituminosas modificadas con polvo de caucho, durante los últimos años la Consejería de Fomento de la Junta de Andalucía las ha aplicado en las capas de rodadura de algunos tramos de carretera con elevado volumen de tráfico y condiciones climáticas desfavorables. Para evaluar estos materiales se ha realizado, en colaboración con el Laboratorio de

Ingeniería de la Construcción de la Universidad de Granada, un estudio sobre la evolución de las prestaciones mecánicas de estas mezclas bituminosas durante su vida útil en comparación con las mezclas tradicionales modificadas con polímero SBS. Para ello, se ensayaron en el laboratorio testigos extraídos directamente de la capa de rodadura del pavimento en diferentes fechas, determinando la evolución de parámetros importantes como la densidad, rigidez o resistencia a la rotura por fatiga. Al igual que para los betunes, en esta tesis se resumen los principales resultados obtenidos para las mezclas hasta el momento.

Sin embargo, a pesar de los beneficios ofrecidos por modificadores sostenibles como el polvo de caucho, el aumento en la viscosidad del ligante que causa, limita la trabajabilidad de las mezclas asfálticas, ya que requieren una temperatura de fabricación más alta y más energía de compactación, siendo por tanto más sensibles a temperaturas bajas durante la construcción del pavimento [50]. Todo ello implica un mayor riesgo a la hora de aplicar estos materiales en climas fríos o en situaciones que impliquen largas distancias de transporte. Por lo tanto, la aplicación de mezclas con polvo de caucho podría verse limitada en estas circunstancias, pudiendo tener también impactos económicos y ambientales negativos debido a la necesidad de una temperatura de fabricación más alta.

Para abordar esta cuestión, el tercer artículo comprende un proyecto de investigación conjunto llevado a cabo por la Consejería de Fomento de la Junta de Andalucía, la empresa Construcciones Pérez Jiménez, S.L., y el Laboratorio de Ingeniería de la Construcción de la Universidad de Granada, que se ha centrado en desarrollar una mezcla asfáltica sostenible de altas prestaciones fabricada con PNFVU a baja temperatura (mediante el uso de aditivos para obtener mezclas asfálticas semicalientes) [51-53]. El objetivo de este proyecto era obtener un material que pudiera ser utilizado como capa de rodadura en la rehabilitación de una vía sometida a un alto volumen de tráfico y condiciones climáticas severas. Esta tesis presenta finalmente los principales resultados de la etapa de laboratorio para el desarrollo de esta mezcla (a nivel de ligante y de mezcla), de la fase de producción en planta, y de la aplicación en la rehabilitación de un tramo de pavimento en la autovía A-92 en la provincia de Granada.

Por todo ello, dado que tradicionalmente el estudio de la evolución de las propiedades mecánicas de ligantes bituminosos no ha sido estudiado ni contemplado en el diseño y selección de las soluciones de conservación de firmes de carreteras (de la misma manera no se ha tenido en cuenta el impacto que diferentes condiciones climatológicas pudieran tener en éstas), se hace necesario el análisis de la evolución de las propiedades mecánicas de diferentes tipos de ligantes y mezclas bituminosas expuestos a distintas condiciones climatológicas, evaluando así el efecto combinado que la temperatura de servicio y el envejecimiento pueden tener en su respuesta mecánica a largo plazo, y tratando de estimar las situaciones más idóneas para acometer la rehabilitación del material (optimizando así las tareas de conservación de carreteras).

Por ultimo, se realiza un estudio económico para valorar los costes de producción de estas mezclas sostenibles en comparación con las fabricadas por métodos tradicionales.

# 2. OBJETIVOS.

El objetivo principal de esta tesis es estudiar las propiedades mecánicas de materiales asfálticos en servicio en función de la carga de tráfico y la climatología, con la finalidad de ofrecer soluciones óptimas para conservación de firmes de carreteras.

Como objetivos secundarios se establecen los siguientes:

1. Estudiar el envejecimiento real de los betunes asfálticos modificados para capa de rodadura durante su vida de servicio, estando estos expuestos a varios agentes, incluyendo gradientes de temperatura, la presencia de agua y la oxidación.

2. Evaluar la evolución del comportamiento mecánico real de mezclas asfálticas en capa de rodadura de carreteras sometidas a condiciones climáticas y de tráfico severas.

3. Valorar el uso de mezclas asfálticas sostenibles de altas prestaciones como solución en la construcción y rehabilitación de pavimentos de carretera.

4. Estimar el coste económico de la implementación de las mezclas sostenibles objeto de esta investigación en relación a las mezclas tradicionales.

# 3. METODOLOGÍA.

## 3.1. Materiales.

Para el análisis de las mezclas bituminosas fabricadas con betunes modificados con PNFVU se han estudiado cuatro tramos de vías de gran capacidad de la Red de Carreteras de Andalucía. Dos de ellos en la autovía A-316 en Jaén, con 5 km de longitud cada uno aproximadamente, y los otros dos en la autovía A-92 en Granada, con 13 km aproximadamente cada uno (Figura 3.1). Estos cuatro tramos de carretera se construyeron utilizando una capa de rodadura de 3 cm de espesor de hormigón bituminoso BBTM 11B PMB45/80-60C. Dicha mezcla asfáltica está compuesta por un esqueleto mineral con un tamaño máximo de árido de 11 mm y fabricada con un ligante asfáltico PMB45/80-60C, modificado con PNFVU [54].

**Figura 3.1.** Localización de tramos de estudio.

En los tramos A-316-I, A-92-I y A-92-II se utilizó el mismo betún: un ligante modificado en la misma refinería mediante la adición de PNFVU al betún (CRMB), que finalmente era llevado a la planta asfáltica para la fabricación de las mezclas [55]. Por su parte, en el tramo A-316-II se utilizó un ligante modificado producido de manera continua en la propia planta asfáltica (CRMB (CB)), donde el polvo de caucho se agregaba al betún en un tanque previo, y se incorporaba finalmente al mezclador de la planta [55]. Esta mezcla se empleó para evaluar cómo se comportaban los diferentes tipos de CRMB en las mismas condiciones de servicio. En todos los tramos de carretera estudiados se ha construido también un subtramo de aproximadamente 400 m de longitud con una BBTM 11B PMB45/80-60 y fabricado con el mismo esqueleto mineral pero con un betún modificado con el polímero convencional SBS (SBSMB). Estas secciones de referencia se construyeron una al lado de la otra para garantizar las mismas condiciones ambientales y de tráfico en las capas de rodadura.

Todas las mezclas BBTM 11B utilizadas en los diferentes tramos se fabricaron con el mismo contenido de ligante (4,8% del peso total de la mezcla) y similar contenido de huecos (15 ± 0,5%) con el fin de evitar que estas variables afectaran al estudio realizado. Las condiciones más severas en cuanto a tráfico y clima se dieron en la A-92-I, donde transitan más de 3000 vehículos pesados al día y durante 5 meses al año es común la presencia de nieve y hielo, así como el empleo de fundentes para deshielo. Por el contrario, ambos tramos de la A-316 ofrecían condiciones de servicio menos severas con menos de 600 vehículos pesados al día y sin apenas presencia de nieve/hielo en la superficie de la carretera.

Todas las fórmulas de trabajo ofrecieron propiedades similares (contenido de ligante, densidad e índice de de huecos), al igual que el comportamiento mecánico, medido éste mediante ensayos de laboratorio realizados sobre muestras obtenidas directamente en las plantas asfálticas utilizadas durante la construcción de los tramos de carretera estudiados. Además, hay que destacar que no hubo diferencias significativas entre ellas en cuanto a costes de producción, trabajabilidad y homogeneidad del betún.

Por último, para la obtención de mezclas asfálticas sostenibles de altas prestaciones, el tipo de mezcla seleccionada fue una BBTM 11B [56], dentro del tramo A-92-I. A las dos mezclas fabricadas a 175°C con el mismo esqueleto mineral y contenido de ligante (una utilizando CRMB y otra usando SBSMB), descritas anteriormente para el tramo A-92-I, se le añadió el desarrollo de una tercera mezcla asfáltica utilizando el mismo esqueleto mineral que las anteriores y CRMB, pero con una reducción de su temperatura de fabricación en 30ºC para obtener una mezcla asfáltica semicaliente. Para ello, durante la fabricación de esta mezcla semicaliente se utilizó un aditivo químico, que hace a la superficie del árido más compatible con el ligante asfáltico y mejora los procesos de fabricación, pavimentación y compactación.

En la Tabla 3.1. se resumen los materiales utilizados.

**Tabla 3.1.** Materiales utilizados para la investigación.

| TRAMO | MATERIALES |
|---|---|
| A-92-I | BBTM 11B caliente con CRMB<br>BBTM 11B caliente con SBSMB<br>BBTM 11B semicaliente con CRMB |
| A-92-II | BBTM 11B caliente con CRMB<br>BBTM 11B caliente con SBSMB |
| A-316-I | BBTM 11B caliente con CRMB<br>BBTM 11B caliente con SBSMB |
| A-316-II | BBTM 11B caliente con CRMB (CB)<br>BBTM 11B caliente con SBSMB |

## 3.2. Métodos.

A continuación se describen los métodos seguidos para el estudio de los betunes, el análisis de las mezclas bituminosas y la evaluación de las mezclas asfálticas sostenibles de altas prestaciones.

### 3.2.1. Estudio de los betunes.

Para el estudio de los betunes se analizaron los tres ligantes (CRMB, CRMB (CB) y SBSMB) antes y después de la fabricación de la mezcla y en diferentes momentos de la vida de servicio del tramo estudiado, mediante extracción de testigos en la zona de rodada. El betún de cada testigo se recuperó mediante el evaporador rotatorio según UNE-EN 12697-3 [57]. Por cada campaña se obtuvieron tres testigos de cada material, y de cada testigo se extrajeron dos muestras de betún.

A continuación, los ligantes recuperados se ensayaron en el Dynamic Shear Rheometer (DSR) mediante ensayos de barrido de frecuencia (de 0,1 a 30 Hz) y de temperatura (de 5 a 80°C) al 10% de amplitud de deformación (según UNE-EN 14.770 [58]). Adicionalmente, se realizó el ensayo Multiple Stress Creep and Recovery Test (MSCRT) a 45, 64 y 70°C, según UNE-EN 16659 [59], donde se aplicaron 30 ciclos de carga de 3,2 kPa y 1 s de duración a las muestras de betún con un período de descanso de 9 s después de cada pulso de carga. A partir de los resultados de las pruebas de barrido de frecuencia y temperatura, se calcularon los parámetros reológicos del módulo complejo (G*) y del ángulo de fase. De igual forma, se mostraron los resultados obtenidos por el MSCRT en base a los parámetros porcentaje de recuperación (R) y complianza no recuperable de fluencia (Jnr). El parámetro R puede identificar y cuantificar cómo está trabajando el polímero en el ligante, mientras que Jnr indica la capacidad de los ligantes asfálticos para resistir deformaciones permanentes.

Por último, en base a los resultados obtenidos para el MSCRT a 45 y 70ºC se usaron otros parámetros innovadores para conseguir una evaluación completa de la respuesta mecánica de los betunes. Así, se obtienen finalmente los valores para el L-index, que mide la susceptibilidad del betún a las cargas, siendo mayor cuanto más susceptible sea el betún a dichas cargas; y el T-index que determina la resistencia del betún a las variaciones de temperatura, siendo mayor cuanto más susceptible sea a dichas variaciones.

### 3.2.2. Análisis de las mezclas bituminosas calientes.

Para el análisis de las mezclas bituminosas, también se extrajeron testigos a lo largo de la vida útil de cada tramo. En cada campaña de extracción se tomaron seis muestras de cada mezcla sobre la zona de rodada. Se determinó su densidad aparente (según UNE-EN 12697-6 [60]) por el procedimiento geométrico. Posteriormente se midió su rigidez a 20°C según UNE-EN 12697-26 (anexo C) [61]. Y finalmente se midió la resistencia a rotura por fatiga mediante el ensayo UGR-FACT (Fatigue Asphalt Cracking Test) de la Universidad de Granada [62]. Mediante este último ensayo se inducen esfuerzos combinados en los testigos (flexión, tracción y cortante) similares a las cargas de servicio del pavimento. A partir de los desplazamientos medidos y del número de ciclos de carga necesarios para producir su rotura, se obtiene la resistencia a fatiga de los materiales.

### 3.2.3. Evaluación de las mezclas asfálticas sostenibles de altas prestaciones.

Para la evaluación de mezclas asfálticas sostenibles de altas prestaciones, el estudio se dividió en tres etapas principales:

1. Estudio de laboratorio (evaluación de ligantes y diseño de mezclas asfálticas).
2. Análisis de la reproducibilidad de la mezcla en planta.
3. Aplicación de la mezcla en un tramo de prueba.

La primera etapa, realizada en laboratorio, consistió en evaluar las características de ambos tipos de ligantes (CRMB y SBSMB) así como las propiedades de las mezclas diseñadas. Para evaluar el comportamiento reológico del CRMB en comparación con el SBSMB tradicional, se midió el módulo complejo y el ángulo de fase a diferentes temperaturas (10, 20, 30, 40, 45, 52, 58, 64, 70 y 80°C para realizar un análisis preciso de la respuesta reológica de los dos ligantes bajo gradientes térmicos severos), y con un rango de frecuencias de 0,1 Hz a 20 Hz, utilizando el DSR a través de una carga de cizallamiento a una amplitud constante de tensión del 0,1 % (usando dos muestras por cada betún).

Con respecto al diseño de las mezclas calientes con CRMB y SBSMB, los ensayos de sensibilidad al agua [63], deformación en pista [64], densidad aparente [60], y contenido de huecos [65], se realizaron para determinar el contenido óptimo de ligante. A continuación, y utilizando el mismo diseño que el utilizado para la mezcla caliente con CRMB, se evaluó la trabajabilidad de la mezcla semicaliente con CRMB a temperaturas de fabricación más bajas (150°C y 130°C) en comparación con la mezcla caliente con CRMB (que fue fabricada a 175°C). Para ello se analizó la densidad de las mezclas en función de la energía de compactación a diferentes temperaturas (utilizando un compactador giratorio), evaluando el módulo de rigidez a 20°C [61] y la pérdida de partículas a 25°C [66] de las probetas obtenidas tras el proceso de compactación. Además, una vez seleccionada la temperatura de fabricación más adecuada para la mezcla semicaliente, se compararon sus propiedades y prestaciones mecánicas con las mezclas calientes con CRMB y SBSMB, utilizando los mismos ensayos descritos anteriormente (sensibilidad al agua, deformación en pista, densidad aparente y contenido de huecos). El módulo de rigidez se midió mediante el Indirect Tensile Stiffness Modulus Test (ITSM), tal y como se describe en la norma UNE-EN 12697-26 (Anexo C). Para la realización del ensayo completo se fabricaron tres probetas para cada una de las mezclas estudiadas.

En la segunda etapa de estudio, después del diseño y evaluación de las mezclas a nivel de laboratorio, se ensayaron distintos procesos de mezclado en una planta asfáltica real para las tres mezclas y probar así su reproducibilidad. Para ello, después de su fabricación en planta, se tomaron muestras para evaluar su respuesta mecánica en el laboratorio mediante los ensayos de sensibilidad al agua [63] y deformación en pista [64]. Adicionalmente, para evaluar su comportamiento bajo acciones climáticas severas, se realizó el ensayo de pérdida de partículas [66]. Por último, la capacidad portante de las mezclas fabricadas en planta se evaluó mediante el ensayo de rigidez [61] a 5, 20 y 40°C; la resistencia a la rotura se evaluó a bajas temperaturas utilizando el Thermal Stress

Restrained Specimen Test (TSRST) [67]; y la rotura por fatiga se evaluó mediante el UGR-FACT a 10, 20 y 30°C [68, 69].

En la tercera fase del estudio, las mezclas se emplearon para la rehabilitación del tramo A-92-I. La elección de este tramo se hizo de acuerdo a criterios ambientales y técnicos. En cuanto al primero de estos criterios, el tramo estaba situado en un puerto de montaña en un parque natural donde el uso de mezclas fabricadas con materiales reciclados y a bajas temperaturas ayudaría a reducir los impactos negativos causados por la conservación de carreteras. En cuanto al segundo criterio, las mezclas se evaluaron en condiciones extremas debido al alto volumen de tráfico (más de 18.000 vehículos/día). Además, este tramo fue ideal para evaluar la trabajabilidad real de la mezcla semicaliente ya que la distancia de la planta asfáltica a la obra fue de aproximadamente 1 hora. Las temperaturas de puesta en obra estuvieron entre 12 y 28°C. Finalmente, para completar la evaluación del comportamiento de la mezcla semicaliente respecto a las convencionales, se extrajeron una serie de testigos para evaluar su densidad aparente [60] tras la compactación, mientras que también se realizaron los ensayos de rigidez [61] y UGR-FACT (a 20°C) para evaluar su respuesta mecánica.

### 3.2.4. Valoración económica de las tecnologías de fabricación de mezclas asfálticas sostenibles de altas prestaciones.

Para concluir la investigación se ha llevado a cabo una estimación del coste económico de implementación de las tecnologías sostenibles estudiadas en esta tesis doctoral: mezclas asfálticas sostenibles con PNFVU fabricadas a baja temperatura mediante el empleo de aditivos. Para ello, se ha analizado el proyecto y obra de rehabilitación de una carretera en Andalucía (A-4028), considerando el coste del aditivo utilizado para la fabricación de la mezcla semicaliente y el del ligante modificado con PNFVU, además de los costes energéticos (consumo de combustible) de la planta asfáltica correspondiente.

# 4. RESULTADOS.

## 4.1. Ageing of crumb rubber modified bituminous binders under real service conditions.

Este capítulo está basado en la siguiente publicación: Francisco Javier Sierra-Carrillo del Albornoz; Fernando Moreno Navarro, F.; Miguel Sol-Sánchez; María del Carmen Rubio-Gámez; Leticia Saiz; **Ageing of crumb rubber modified bituminous binders under real service conditions**. *Sustainability 2022, 14, 11189. https://doi.org/10.3390/su141811189*.

### 4.1.1. Abstract.

Due to their environmental advantages, crumb rubber modified asphalt binders constitute an interesting alternative to conventional binders for road surfaces of a more durable and sustainable nature. However, in practice, they remain less commonly used than conventional polymer modified binders. This research aims to study the real ageing of crumb rubber modified asphalt binders during their service lives when exposed to various factors, including temperature gradients, the presence of water and oxidation. To this end, research was conducted on a selection of highways built with these binders and located in regions with severe climatic and traffic conditions. The binders from cores of highway surface layers were recovered and tested using the DSR (Dynamic Shear Rheometer) to determine the evolution of the rheological parameters. Crumb rubber modified asphalt binders were studied in comparison with traditional polymer modified bitumen. The analysis of the complex modulus and phase angle was conducted based on frequency and temperature sweep tests, while the evolution of the elastic recovery, Jnr, L-Index and T-Index were assessed from the multiple stress creep and recovery test. The results obtained indicate that crumb rubber modified binders show similar ageing and rheological parameters to those of conventional polymer modified bitumen, even under severe traffic and climate conditions. Furthermore, it was observed that, at high temperatures, the effect caused by real service life ageing was different to that obtained in the laboratory through the RTFO and PAV tests.

### 4.1.2. Introduction.

Crumb rubber from end-of-life tyres has been used as a modifier in bituminous materials around the world for decades [1]. This modifier both improves the mechanical performance of asphalt materials via increasing their resistance to fatigue cracking and to plastic deformations and reduces their ageing and rolling noise [2–7]. In turn, this results in road surfaces of greater durability with less need for maintenance. Countries, including the USA, have a wide experience with the use of crumb rubber modified asphalt mixtures in all types of roads and climates and have proved the aforementioned advantages of their application [8–13].

In addition to the technical advantages offered by crumb rubber in asphalt materials, it also offers a major opportunity to reduce the environmental impact caused by road construction and rehabilitation [14–16]. The incorporation of crumb rubber in asphalt materials enables the valorization of a waste product that most countries generate in huge quantities [17]. In turn, it aligns with the principles of a circular economy and, therefore, contributes towards global sustainable development targets and the more effective management of natural, economic and energy resources.

However, despite all these environmental and technical advantages, the application of crumb rubber modified bitumen (CRMB) in Spain remains limited, especially in surface layers and high-volume-traffic roads [18,19]. One of the main reasons for this lies in the lack of information and tracking of the experiences already conducted. The mechanical performance of these experiences has not been studied over the years, leading to road administrations having insufficient reasoning to select these abundant waste materials instead of traditional Styrene–Butadiene–Styrene (SBS) modified binders (SBSMB), which have decades of success and reliable use.

Therefore, to increase the confidence in crumb rubber-based binders while also supporting sustainable development and the circular economy, this paper aims to undertake an in-depth analysis of the rheological properties of crumb rubber modified bitumen under real traffic and climate conditions. To achieve this aim, a Public–Private–Academic Partnership was carried out with 3 members: (1) the government of Andalusia (Spain), which has been utilising these materials in the surface layers of highway sections in recent years; (2) SIGNUS (a non-profit organisation in charge of the management of the used tyres in Spain); and (3) the Laboratory of Construction Engineering of the University of Granada. Together, the evolution of the mechanical performance of these materials during their service life was studied in comparison to the traditional SBS modified binder. To this end, CRMB and SBSMB were extracted from cores directly obtained from the surface layers of two highways in this region on different dates. The binders were subsequently tested in the laboratory using various rheological tests (frequency and temperature sweeps and multiple stress creep and recovery tests, using the DSR (Dynamic Shear Rheometer)) to determine the evolution of their mechanical properties during their service life. These roadways are subject to some of the most unfavourable conditions in the region in terms of climate and traffic. This paper summarises the main results obtained from this research work.

### 4.1.3. Methodology.

#### *4.1.3.1. Materials.*

This paper focuses on the study of 4 sections (Figure 4.1.1) of the high-capacity road network of Andalusia (Spain). Two of these sections were part of the A-316 highway (approximately 5 km each, Jaén) and the other two of the A-92 highway (approximately 13 km each, Granada). These four highway sections were constructed using a 3 cm-thick surface layer using a BBTM 11B PMB 45/80-60 C; an asphalt mixture composed of a gapgraded mineral skeleton with a maximum aggregate size of 11 mm and manufactured with a crumb rubber modified asphalt binder PMB 45/80-60 C [20]. In sections A-316-I, A-92-I and A-92-II, the same terminal blend of CRMB was used: a modified binder manufactured in a refinery where the crumb rubber was added to the bitumen, mixed at high speed and eventually with other additives, and then collected in another tank where the blend stayed to allow the reaction and was finally transported to the asphalt plant [21]. This blend was produced from the same refinery in order to assess better how the same CRMB would perform under various service conditions. Meanwhile, in the A-316-II section, a continuous blend of CRMB was used: a modified binder produced in a continuous operation in the asphalt plant, where the crumb rubber was added to the bitumen in a blending tank, mixed at high speed, which enabled the reaction between the two compounds during the blending, and then incorporated into the mixer of the plant [21]. This blend was employed to evaluate how different types of CRMBs behaved under the same service conditions. In all the highway sections studied, a sub-section of approximately 400 m in length was also constructed using a BBTM 11B PMB 45/80-60 and manufactured with the same mineral skeleton but using a conventional SBS polymer modified bitumen. These reference sections were constructed side by side to ensure the same environmental and traffic conditions as the crumb rubber modified asphalt layers.

**Figure 4.1.1.** Schema of the highway section locations.

All the BBTM 11B mixtures used in the different sections were manufactured with the same binder content (4.8% of the total weight of the mixture) and a similar air void content (15±0.5%) in order to prevent these variables from affecting the study conducted. The service conditions of the highway sections studied are summarised in Table 4.1.1. It can be observed that the most severe conditions in terms of traffic and climate occurred in A-92-I, where more than 3000 heavy vehicles pass every day and the presence of snow, frost and chemical substances for de-icing purposes is common for 5 months every year. Conversely, both the A-316 cases offered less severe service conditions with fewer than 600 heavy vehicles a day and no presence of snow/ice on the road Surface.

**Table 4.1.1.** Characteristics of the service conditions in the highway sections studied.

| | **A-316-I and A-316-II** | **A-92 - I** | **A-92 – II** |
|---|---|---|---|
| Date of traffic opening | November, 2015 | September, 2017 | July, 2018 |
| Annual Average Daily Traffic (Number of vehicles) | 8,000 | 18,000 | 11,000 |
| Percentage of heavy traffic (over the total number of vehicles) | 8 | 17 | 7 |
| Climate conditions | ~750 m above sea level; Rarely frost/snow over the road surface during autumn/winter; Maximum average temperatures in summer ~36 °C; Minimum average temperatures on winter ~4 °C | ~1400 m above sea level; Very frequent frost/snow over the road surface during autumn/winter; Maximum average temperatures in summer ~30 °C; Minimum average temperatures on winter ~1 °C | ~1100 m above sea level; frequent frost/snow over the road surface during autumn/winter; Maximum average temperatures in summer ~33 °C; Minimum average temperatures on winter ~4 °C |

#### *4.1.3.2. Testing Plan.*

In this study, two different CRMBs (a terminal blend PMB 45/80-60 C and a continuous blend PMB 45/80-60 C that we label CRMB (CB)) were evaluated under the same service conditions (A-316 highway) and compared with a traditional SBSMB. Similarly, the same terminal blend CRMB (PMB 45/80-60 C) was also evaluated under various service conditions (A-316, A-92-I and A-92-II) and compared with the performance offered by a traditional SBSMB. For this purpose, the three binders studied (CRMB, CRMB (CB) and SBSMB) were analysed prior to and subsequent to mixture manufacture. The latter analysis took place at different times (Table 4.1.2) depending on the core extraction campaign. Figure 4.1.2 shows the average densities obtained [22] in the cores extracted in each campaign for the different types of materials. As can be observed, the densities of the asphalt mixtures over time remains constant, which indicates that the possible differences to be found in the ageing are not due to changes produced in the air void content of the mixtures.

**Table 4.1.2.** Dates of the cores extracted from each highway section studied.

| Core Extraction Campaign | A-316-I | A-316-II | A-92 - I | A-92 – II |
|---|---|---|---|---|
| 1 | 37 months<br>(December, 2018) | 37 months<br>(December, 2018) | 18 months<br>(March, 2019) | 11 months<br>(June 2019) |
| 2 | 63 months<br>(February, 2021) | 63 months<br>(February, 2021) | 46 months<br>(July, 2021) | 36 months<br>(July 2021) |

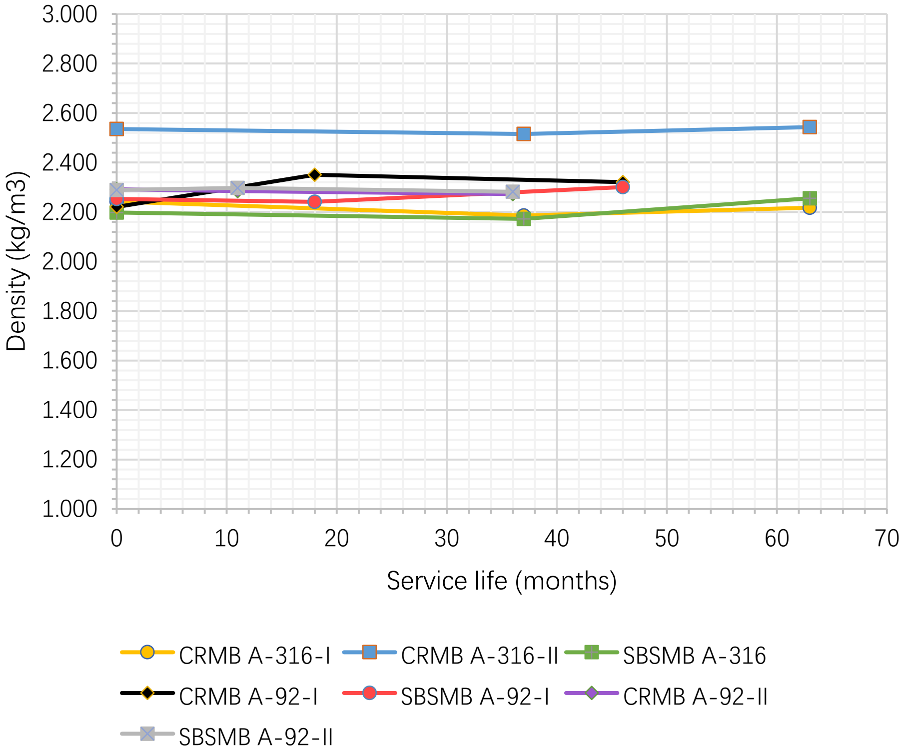

**Figure 4.1.2.** Evolution of the densities of the cores extracted over time.

Once the cylindrical cores were obtained from the wheel path in the highway sections during the periods defined in Table 4.1.2, their asphalt binders were recovered using the rotary evaporator in accordance with UNE-EN 12697-3 [23]. In each campaign and type of material, three cores were obtained, and from each one, two binder samples were obtained (i.e., 6 binder samples were used in each test for each type of material and campaign). The recovered binders were tested in the Dynamic Shear Rheometer (DSR) using frequency (from 0.1 to 30 Hz)) and temperature (from 5 to 80 °C) sweep tests at a 10% strain amplitude (in accordance with to UNE-EN 14,770 [24]). Additionally, the Multiple Stress Creep and Recovery Test (MSCRT) was conducted at 45, 64 and 70 °C, in accordance with UNE-EN 16,659 [25], where 30 load cycles of 3.2 kPa and 1 second of duration were applied to the binder specimens with a rest period of 9 seconds after each load pulse. From the results of the frequency and temperature sweep tests, the Complex Modulus (G*) and phase angle rheological parameters were calculated. Similarly, the results obtained in MSCRT were shown based on the percentage recovery (R) and non-recoverable creep compliance (Jnr) parameters. The parameter *R* can identify and quantify how the polymer is working in the binder, while *Jnr* indicates the capacity of the asphalt binders to resist permanent deformations.

Nonetheless, based on the MSCRT results obtained at 45 and 70 °C, other innovative parameters were also employed to conduct a complete evaluation of the mechanical response of asphalt binders [26]: the non-recoverable strain rate ($\Delta\varepsilon_{nr}$, in %/cycles, Equation 1) and average recovered strain ($RS_{15\text{-}30}$, in %/cycles), which was the average absolute recovered strain from each cycle measured from the 15th cycle to the 30th cycle.

$$\Delta\varepsilon_{nr} = \frac{\varepsilon_{nr30} - \varepsilon_{nr15}}{30-15} \text{ (1)}$$

where $\varepsilon_{nr30}$ is the cumulative non-recoverable deformation after 30 load cycles and $\varepsilon_{nr15}$ is the cumulative non-recoverable deformation after 15 load cycles. This parameter is calculated from the 15th load cycle and the 30th load cycle, which is when the response of the binder becomes more stable. As $\Delta\varepsilon_{nr}$ increases, there is a decrease in the resistance of the binders to permanent deformations under cyclic stress loading.

The Flow index (Equation (2)) is a quantitative measurement of the flow and capacity of the binder to deform under the effects of stress. The higher this value, the lower the capacity of the binder to absorb the stress energy without deforming, regardless of whether such deformation is recoverable. Recovery Capacity (RC, Equation (3)) is a quantitative measurement of the elasticity of the binder (the proportion of the Flexibility index that corresponds to recoverable deformations). The higher this value, the greater the amount of strain that can be recovered by the binder.

$$F = \sqrt{\Delta\varepsilon_{nr}{}^{2} + RS_{15-30}{}^{2}} \text{(2)}$$

$$RC = tan^{-1}\left(\frac{RS_{15-30}}{\Delta\varepsilon_{nr}}\right) \text{(3)}$$

Based on these parameters, the L-index can be calculated, which measures the susceptibility of the binder to the loads (Equation (4)). As F increases, there is an increase in the susceptibility of the materials to stress loads. Meanwhile, as RC increases, there is an increased capacity to recover the changes produced by the loads since the recovered strain rises as the non-recoverable strain rate falls. Thus, as the L-Index increases, the susceptibility of the binder to the loads becomes greater, and therefore there is an increased likelihood of distress appearing due to the passing traffic.

$$L - Index = \frac{F}{tanRC} = \frac{\Delta\varepsilon_{nr}\sqrt{\Delta\varepsilon_{nr}{}^{2} + RS_{15-30}{}^{2}}}{RS_{15-30}} \text{(4)}$$

Moreover, the changes produced in the bitumen due to variations in temperature should also be evaluated. This is particularly important in the case of polymer modifiers since not only do they provide asphalt binders with elastic recovery properties, but they can also reduce thermal susceptibility. As the test temperature increases, the mechanical response of asphalt binders becomes softer and therefore F increases while RC decreases. Thus, under a given variation in temperature (from 45 to 70 °C, in the case of the proposed study), the increment produced in F ($F_{45\text{-}70}$, obtained from the norm of the vector formed by the $\Delta\varepsilon_{nr}$ and $RS_{15\text{-}30}$ values at 45 and 70 °C) and the loss of RC ($RC_{45\text{-}70}$)) can be utilised to determine the temperature susceptibility of the binder evaluated (Figure 4.1.3). Based on these considerations, the T-Index (Equation (5)) can be obtained to determine the resistance of asphalt binders to temperature variations.

$$T - Index = F_{45-70}\frac{RC_{45}-RC_{70}}{RC_{45}}(5)$$

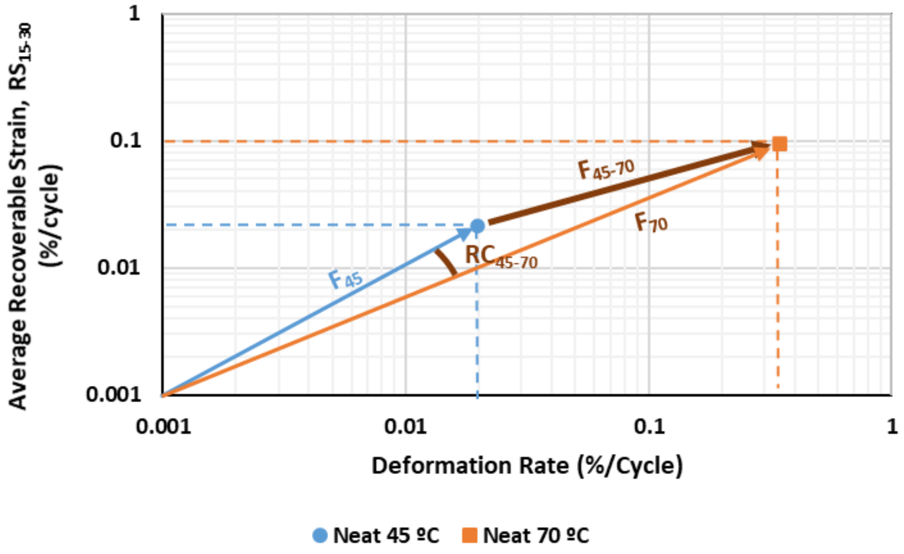

**Figure 4.1.3.** Example of the changes produced in $\Delta\varepsilon_{nr}$ and $RS_{15\text{-}30}$ as a consequence of the increases in temperature.

### 4.1.4. Analysis of Results.

Figures 4.1.4-4.1.6 show the Black diagrams obtained in the frequency and temperatura sweep tests conducted on the asphalt binders from the A-316 highway, where two different types of CRMBs and a traditional SBSMB were evaluated under the same service conditions. Results demonstrate that the three binders suffered a stiffening process during their service life, with a higher complex modulus for the same frequency and temperature over time. These materials also became more elastic at lower temperatures (lower phase angles) and more viscous at high temperatures (higher phase angles), which demonstrated the positive effects of the polymers in the binders (in that they became more elastic at high temperaturas and less brittle at lower temperatures) were less marked due to the ageing suffered during their service life. This made the modified binders become less thermo-rheologically complex due to ageing under real service conditions, which is not observed at the laboratory level when they are aged using an RTFOT (Rolling Thin Film Oven Test) and PAV (Pressure Ageing Vessel) test [27,28]. It should be borne in mind that the variations suffered by the traditional SBSMB are lower than those observed in the CRMB and the CRMB (CB), which could indicate that this binder is less affected by ageing during its service life. These results are in accordance with other results obtained at the laboratory level [27]. Nonetheless, it must also be stated that the fresh CRMBs offered a more elastic performance than did the SBSMB, and the behaviour obtained after ageing was similar for the three binders. No significant differences were found between the results obtained in the two types of CRMBs, which demonstrates that the two processes (terminal and continuous blends) produce materials with similar properties.

These results can easily be observed in the isochrone curves for a fixed frequency (5 Hz) and different temperatures (Figures 4.1.7–4.1.12). The complex modulus of the binders, after several months of service life, was found to have significantly higher values than that obtained for the fresh binders and at lower temperatures. All the binders became more elastic as their service life progressed (lower phase angles), regardless of the type of bitumen and test temperature analysed. This aspect had previously been observed at the laboratory level when using RFTO+PAV tests [27,28]; however, contrary to the laboratory observations, in the case of the CRMB, where no significant differences were observed between the two manufacturing processes, they became more viscous, and therefore more susceptible to plastic deformations, at higher temperatures (higher phase angles), which demonstrated the reduction of the effects of polymers in the binders in that they became thermo-rheologically simpler. In the case of the SBS, in spite of lower service-life temperatures, it also became more brittle (similar to the CRMB) at higher temperatures, which inferred that it was able to maintain the same phase angles as the fresh SBSMB: this was also in contrast with the observations made at the laboratory, where the values of the phase angle in aged binders were reduced regardless of the temperature [27,28].

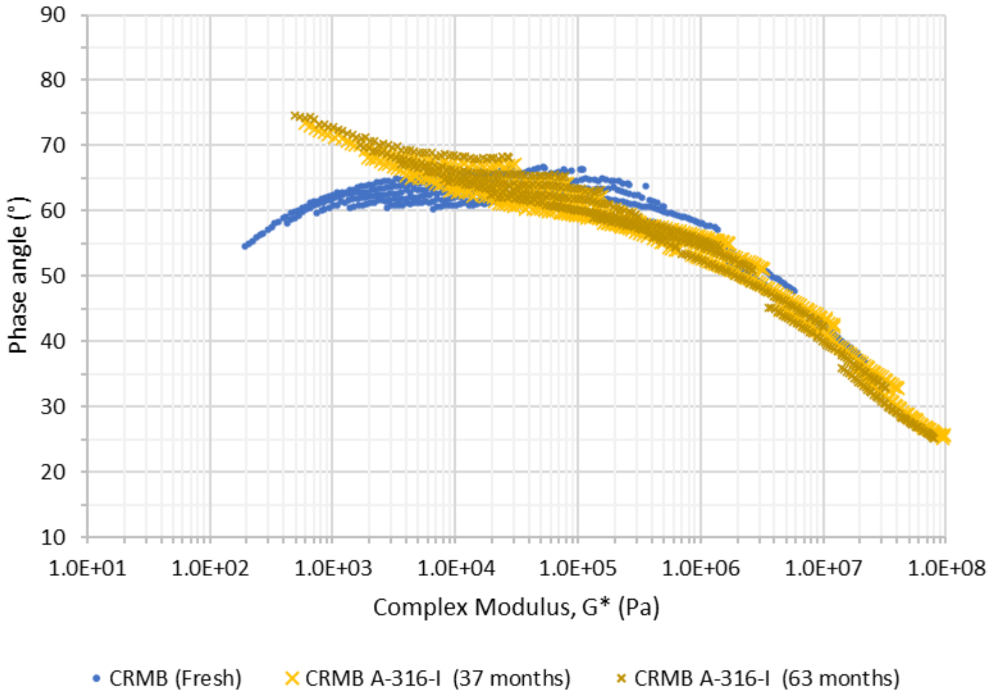

**Figure 4.1.4.** Black diagrams of the CRMB used in the A-316-I at different service-life periods.

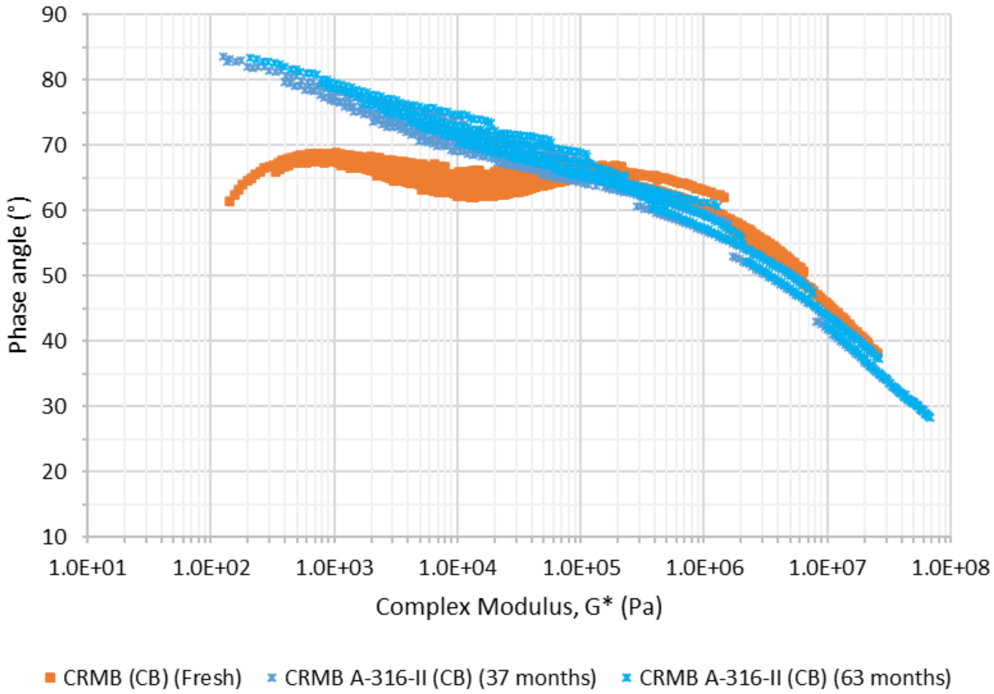

**Figure 4.1.5.** Black diagrams of the CRMB (CB) used in the A-316-II at different service-life periods.

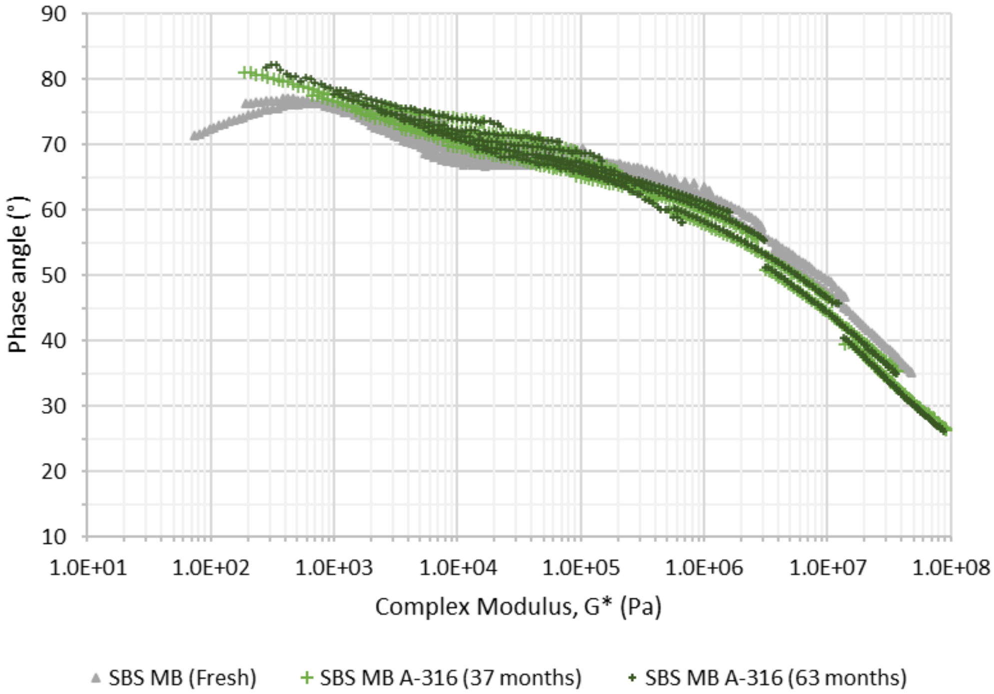

**Figure 4.1.6.** Black diagrams of the SBSMB used in the A-316 at different service-life periods.

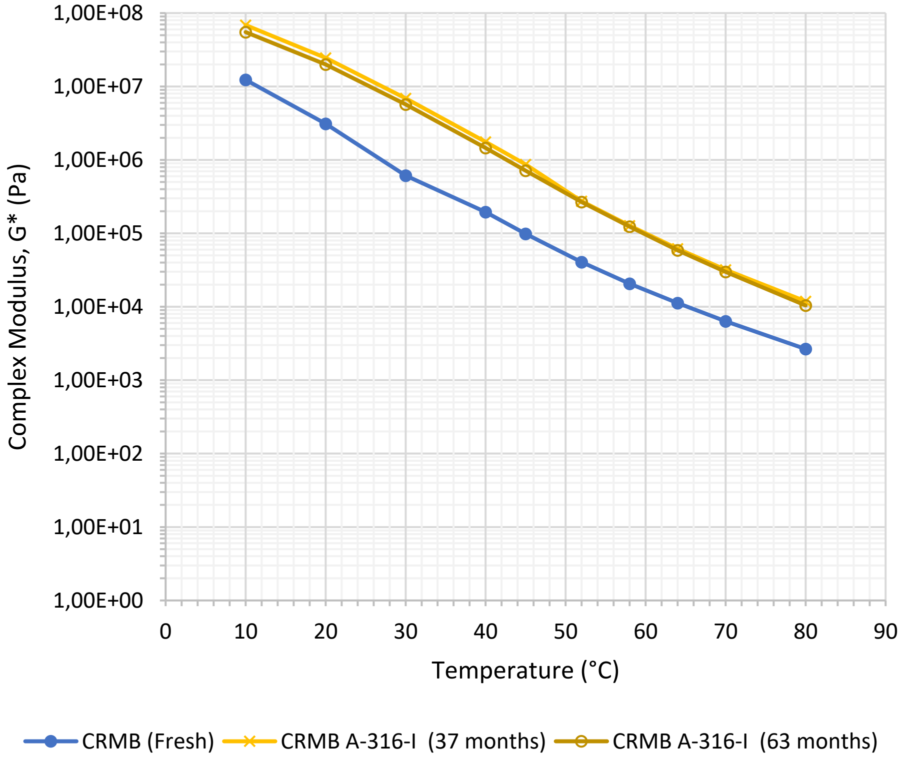

**Figure 4.1.7.** Isochrone curves at 5 Hz of the complex modulus of the CRMB used in the A-316-I at different service-life periods.

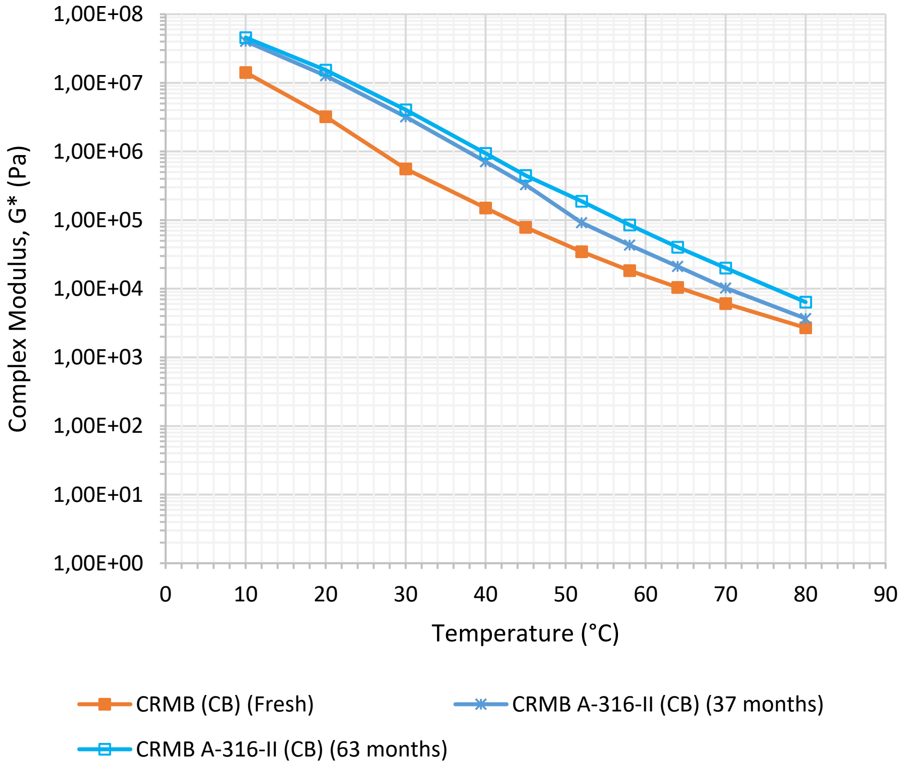

**Figure 4.1.8.** Isochrone curves at 5 Hz of the complex modulus of the CRMB (CB) used in the A-316-II at different service-life periods.

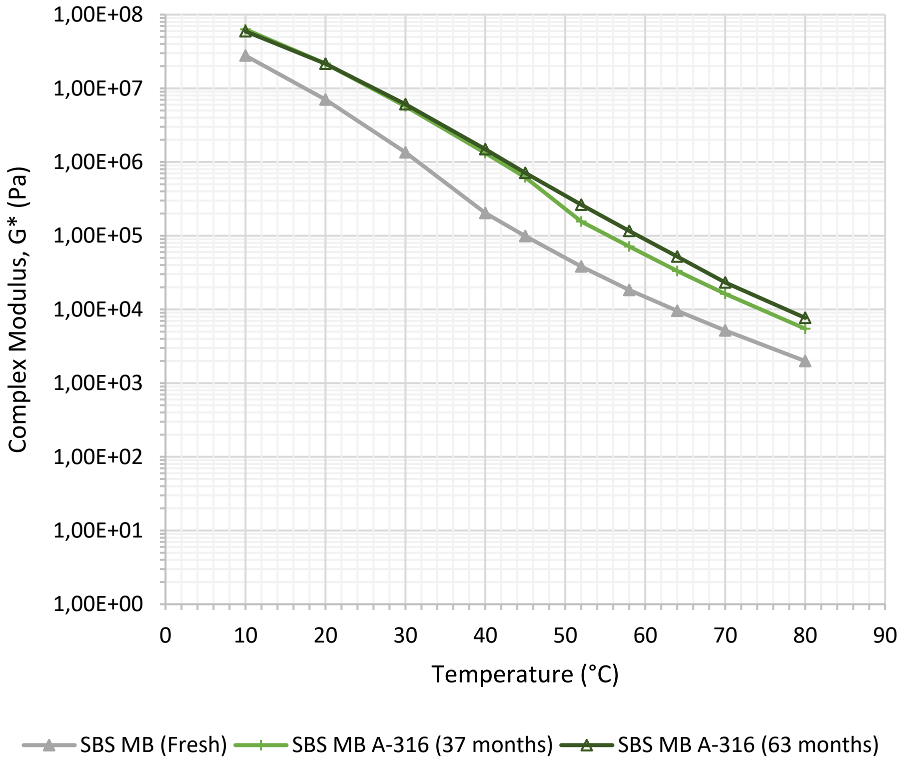

**Figure 4.1.9.** Isochrone curves at 5 Hz of the complex modulus of the SBSMB used in the A-316 at different service-life periods.

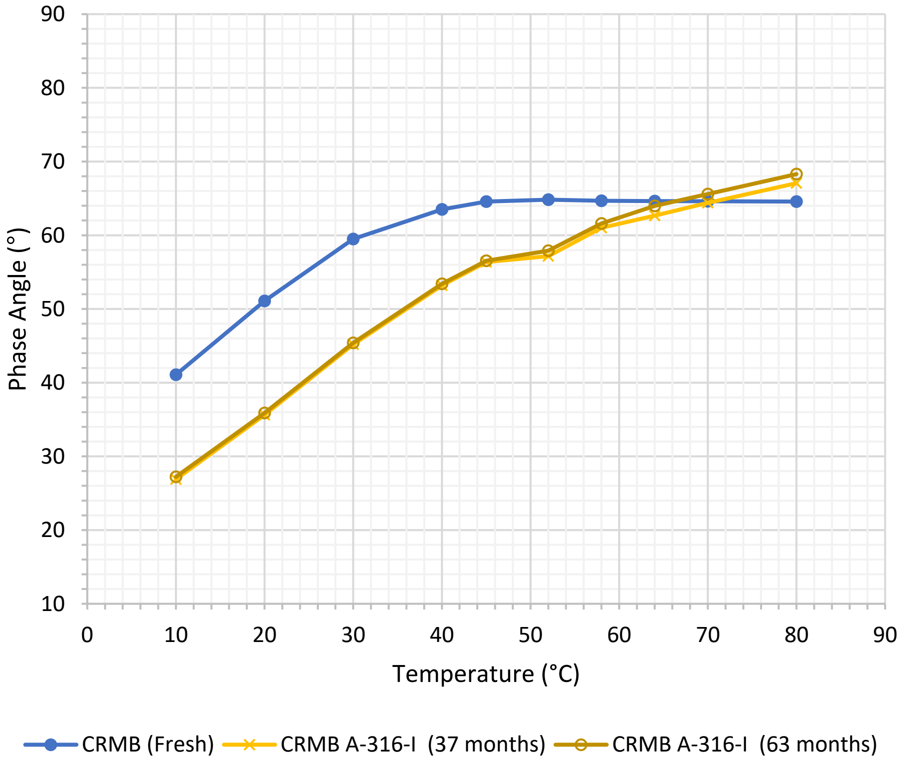

**Figure 4.1.10.** Isochrone curves at 5 Hz of the phase angle of the CRMB used in the A-316-I at different service-life periods.

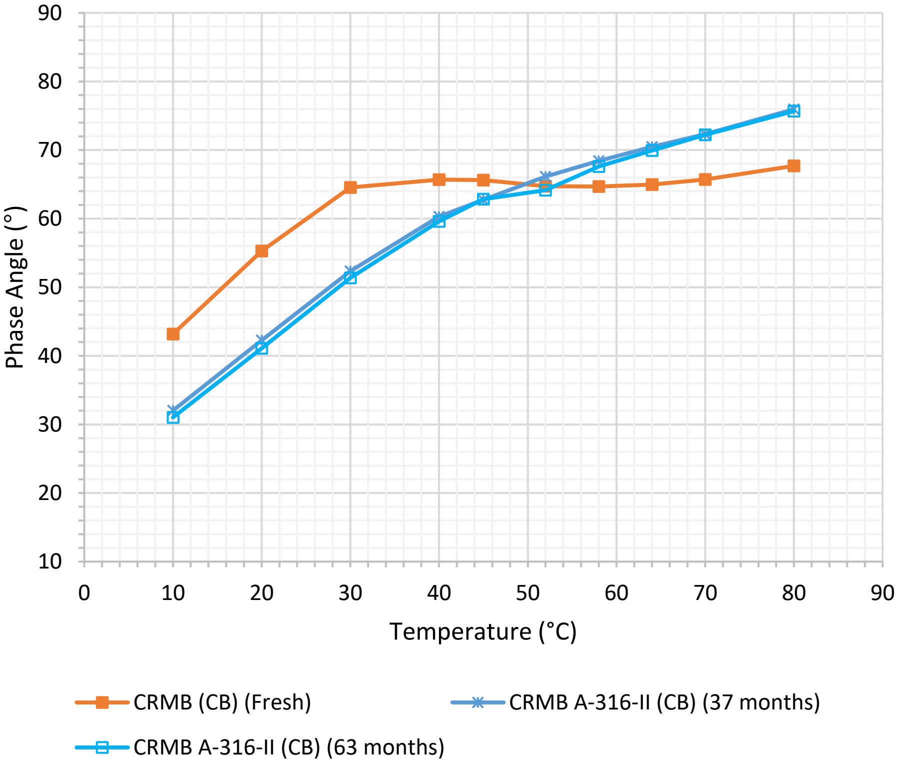

**Figure 4.1.11.** Isochrone curves at 5 Hz of the phase angle of the CRMB (CB) used in the A-316-II at different service-life periods.

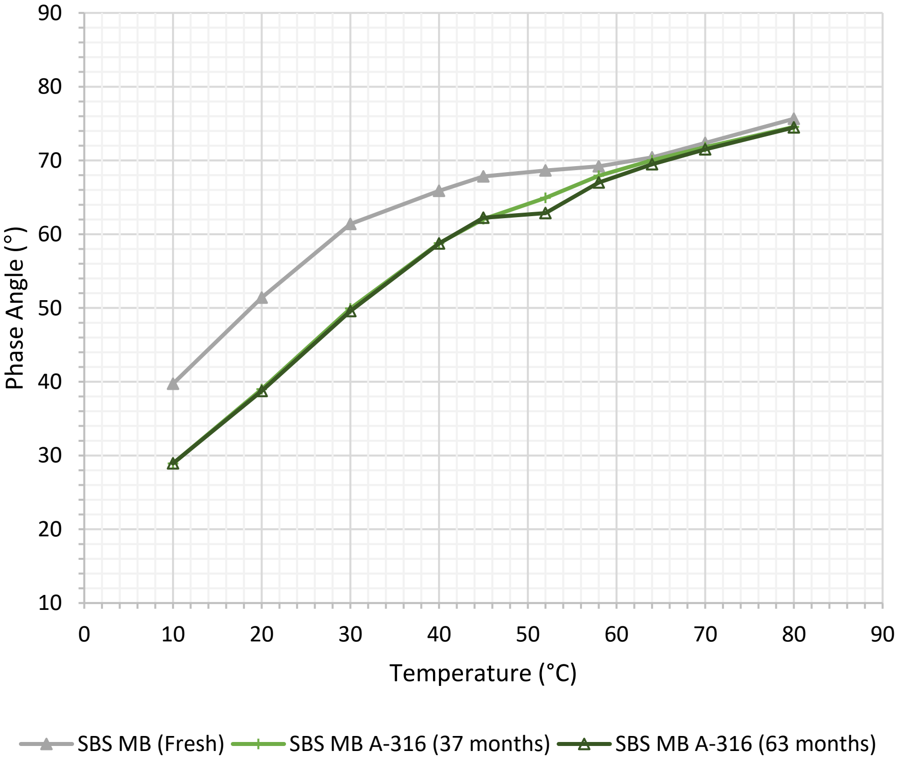

**Figure 4.1.12.** Isochrone curves at 5 Hz of the phase angle of the SBSMB used in the A-316 at different service-life periods.

In the other highway sections studied (A-92-I and A-92-II), the results obtained were in accordance with those observed in the A-316 highway, and no significant differences were presented between the three scenarios investigated (Figures 4.1.13–4.1.16). Both types of modified bitumen (CR and SBS) experienced an increment in their complex modulus regardless of the test temperature (Figures 4.1.17–4.1.19). Furthermore, the CRMB and SBSMB suffered a marked reduction in phase angle at lower temperatures, but only the CRMB resulted in an increase in this parameter at higher temperatures (which again demonstrates both the loss of efficiency of the polymer additive as the service life progresses and the differences between the effect of real ageing and laboratory ageing through RTFOT+PAV). After several months in service, the SBSMB was able to maintain similar phase angle values at higher temperatures than those obtained when tested as fresh SBSMB. However, it is important to highlight that the values obtained from the specimens that underwent higher service temperatures were very similar to those obtained in CRMB since fresh CRMB mixtures were more elastic than fresh SBSMB (Figures 4.1.20–4.1.24).

The MSCR test findings (Figures 4.1.25–4.1.31) corroborated that the stiffening process suffered by the binders during their service life reduced their susceptibility to plastic deformations (lower values of Jnr), regardless of the test temperature and the service conditions: this finding was obtained in all the binders and highway sections studied; it was also in accordance with previous results obtained in the laboratory [29,30]. In contrast, the capacity for recovering from the deformations was found to be different per binder type and service condition. This property was not found to be affected in the case of SBSMB on the A-316 and A-92-II highways. However, the recovery capacity of SBSMB decreased under the service conditions in A-92-I (which presented the most severe conditions), especially at higher temperatures. The CRMB (CB) experienced no changes in recovery capacity in the A-316 highway (the only scenario where it was tested), while the CRMB underwent changes in the three highway sections studied (A-316, A-92-I and A-92-II). This was found to be the case, especially at higher temperatures and under the most severe service conditions in the A-92-I. Finally, it should be borne in mind that while the CRMB was found to be the most affected binder, its performance after ageing was in the same order as (or even better than) that offered by CRMB (CB) and SBSMB.

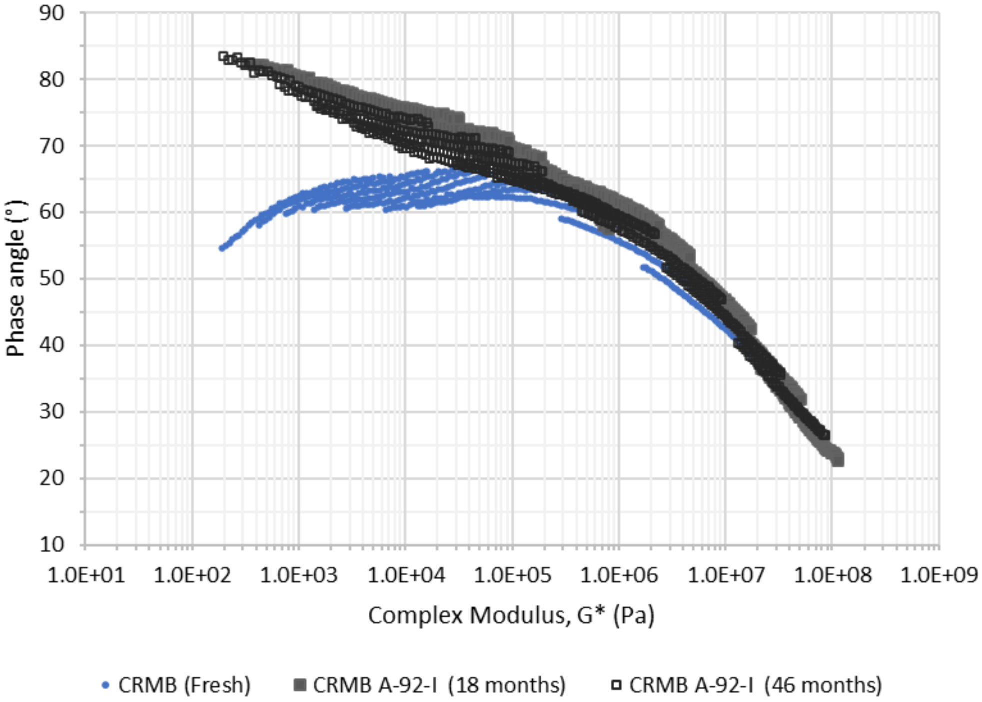

**Figure 4.1.13.** Black diagrams of the CRMB used in the A-92-I at different service-life periods.

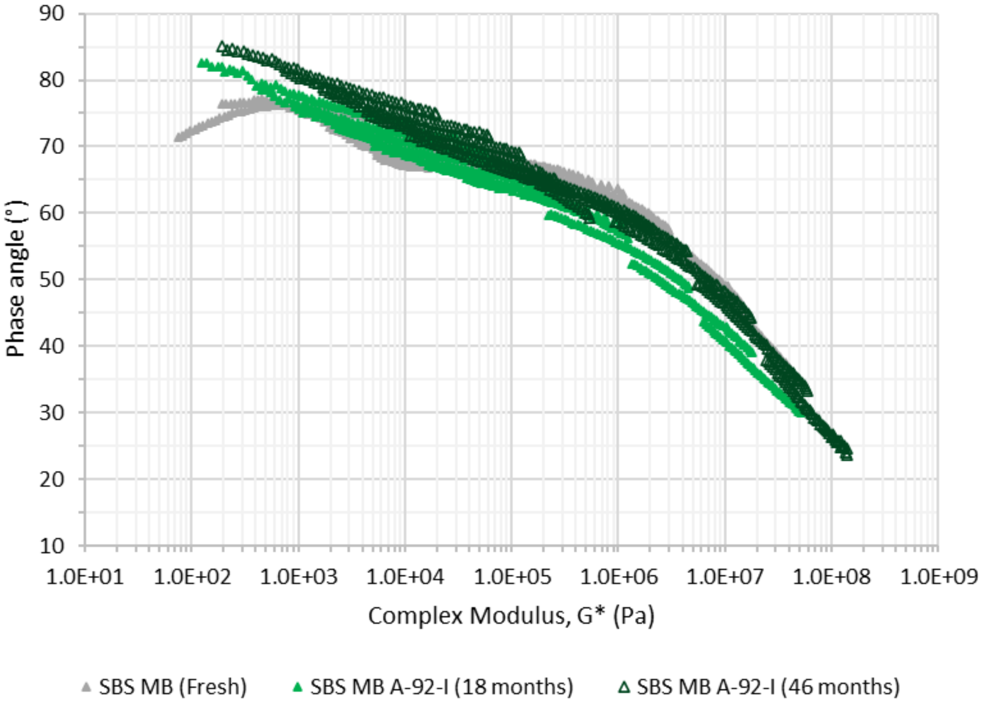

**Figure 4.1.14.** Black diagrams of the SBSMB used in the A-92-I at different service-life periods.

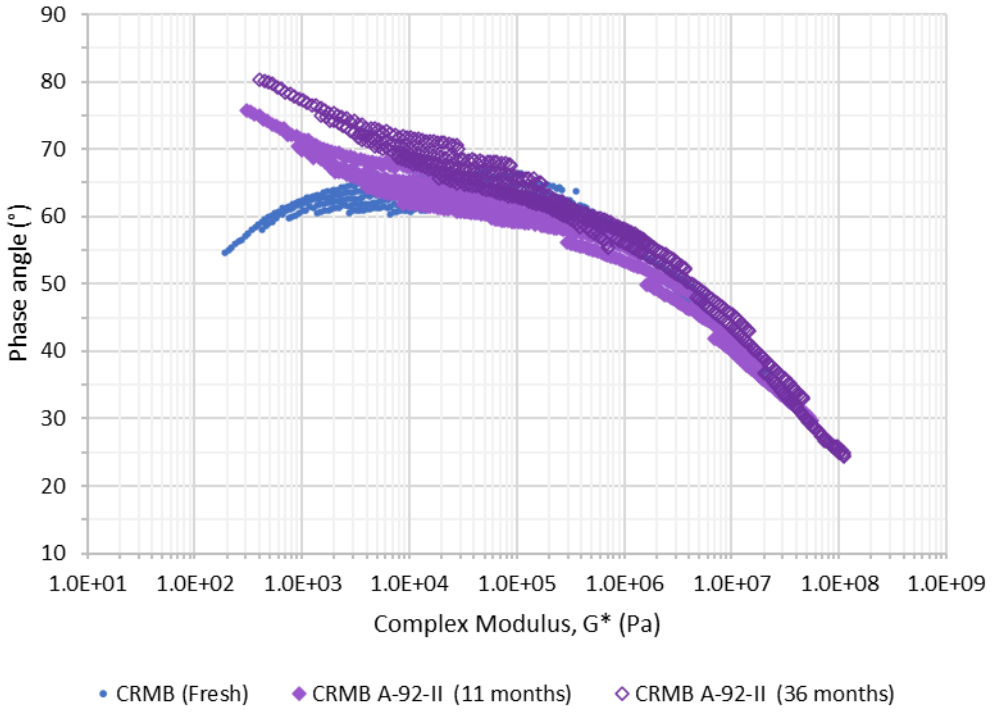

**Figure 4.1.15.** Black diagrams of the CRMB used in the A-92-II at different service-life periods.

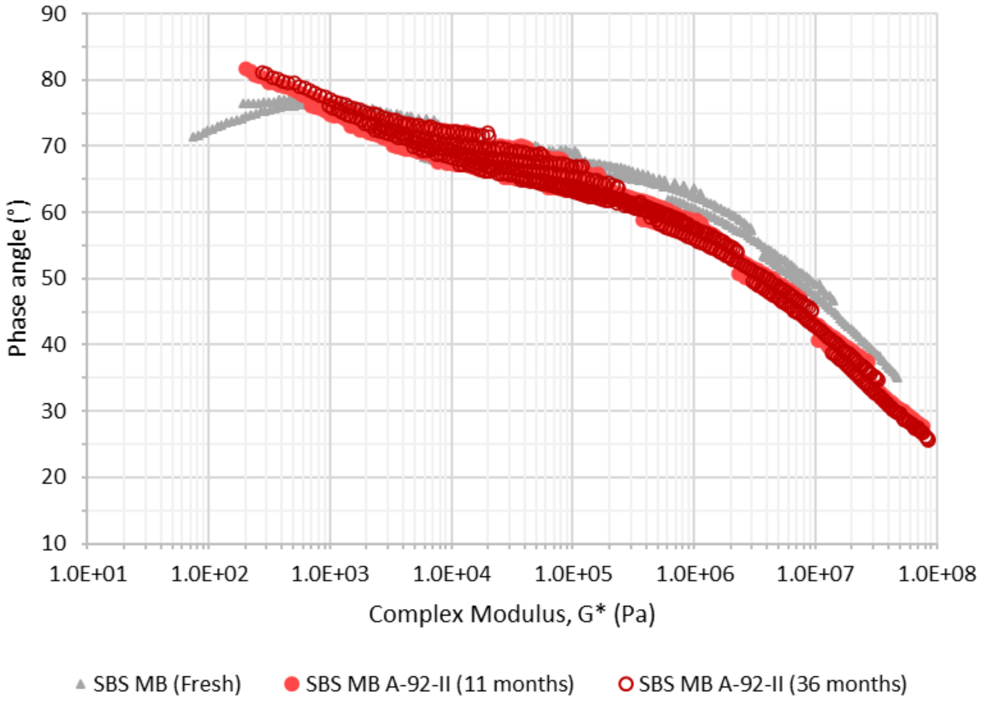

**Figure 4.1.16.** Black diagrams of the SBSMB used in the A-92-II at different service-life periods.

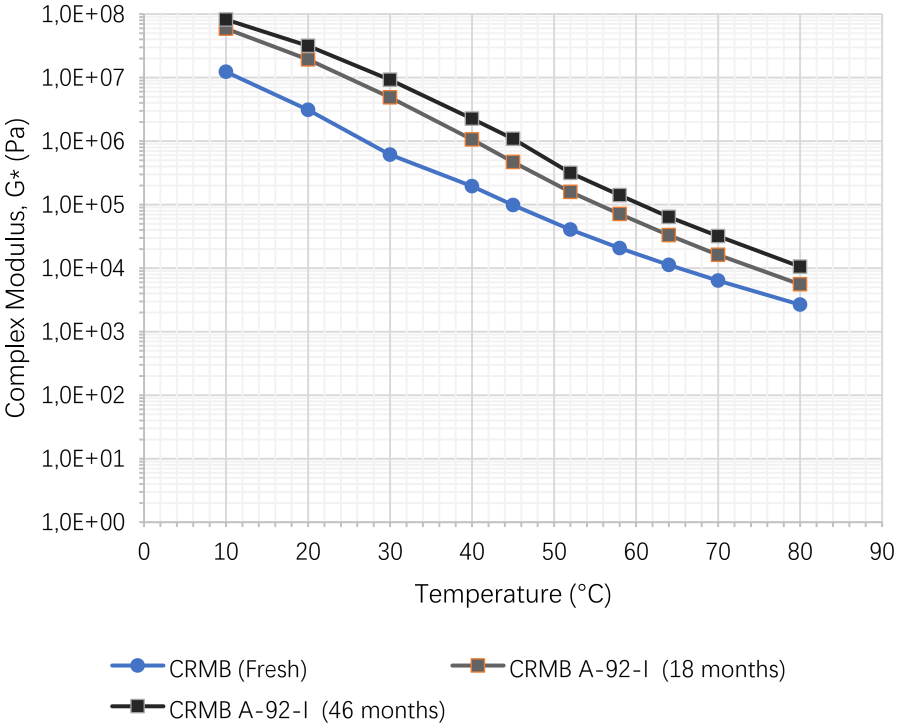

**Figure 4.1.17.** Isochrone curves at 5 Hz of the complex modulus of the CRMB used in the A-92-I at different service-life periods.

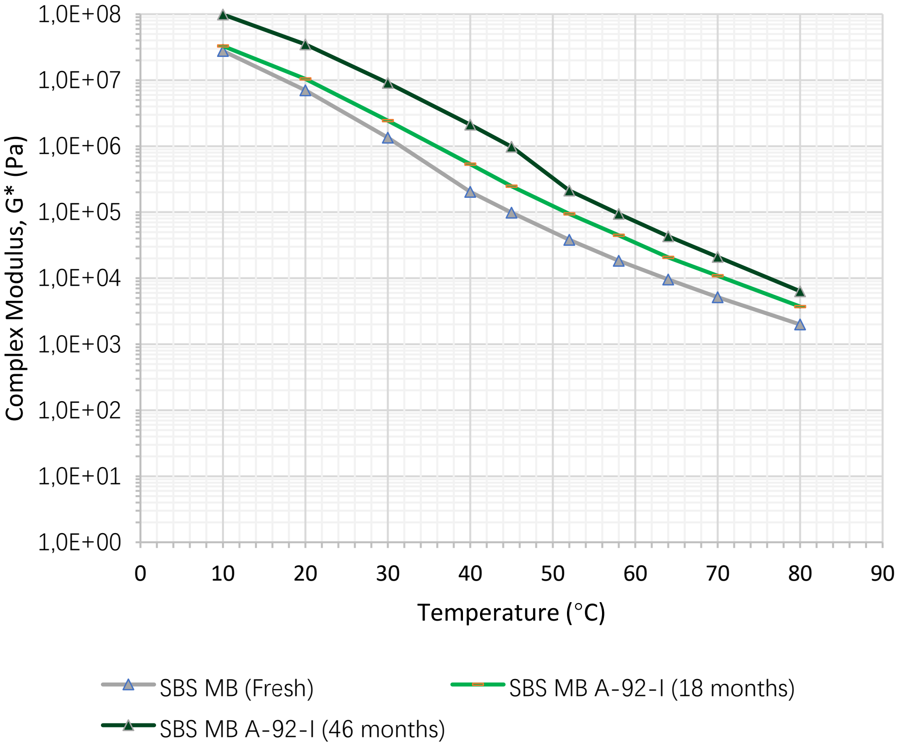

**Figure 4.1.18.** Isochrone curves at 5 Hz of the complex modulus of the SBSMB used in the A-92-I at different service-life periods.

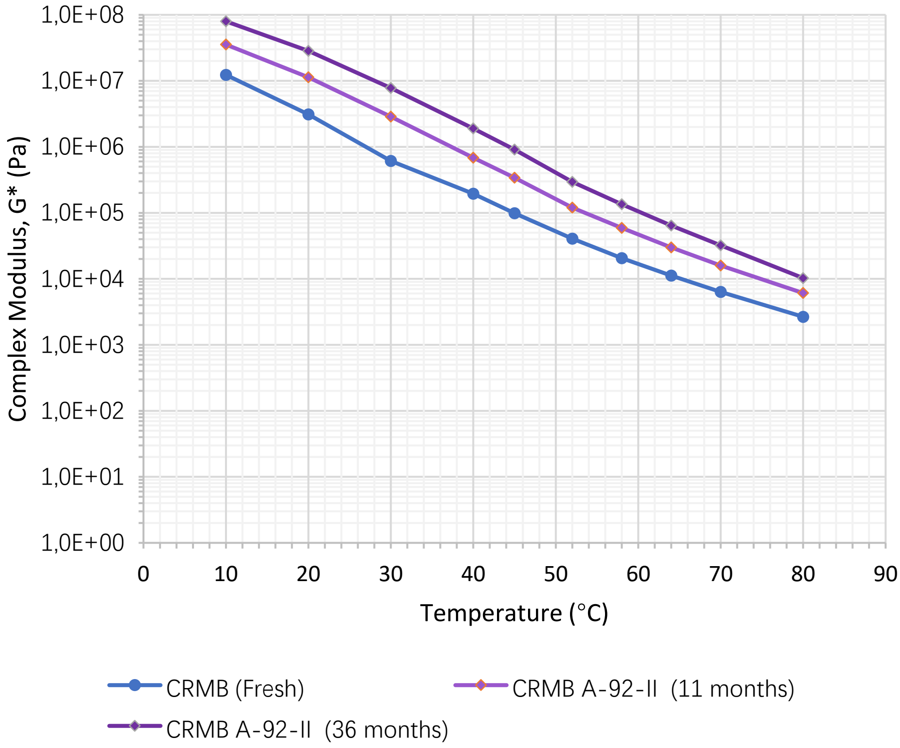

**Figure 4.1.19.** Isochrone curves at 5 Hz of the complex modulus of the CRMB used in the A-92-II at different service-life periods.

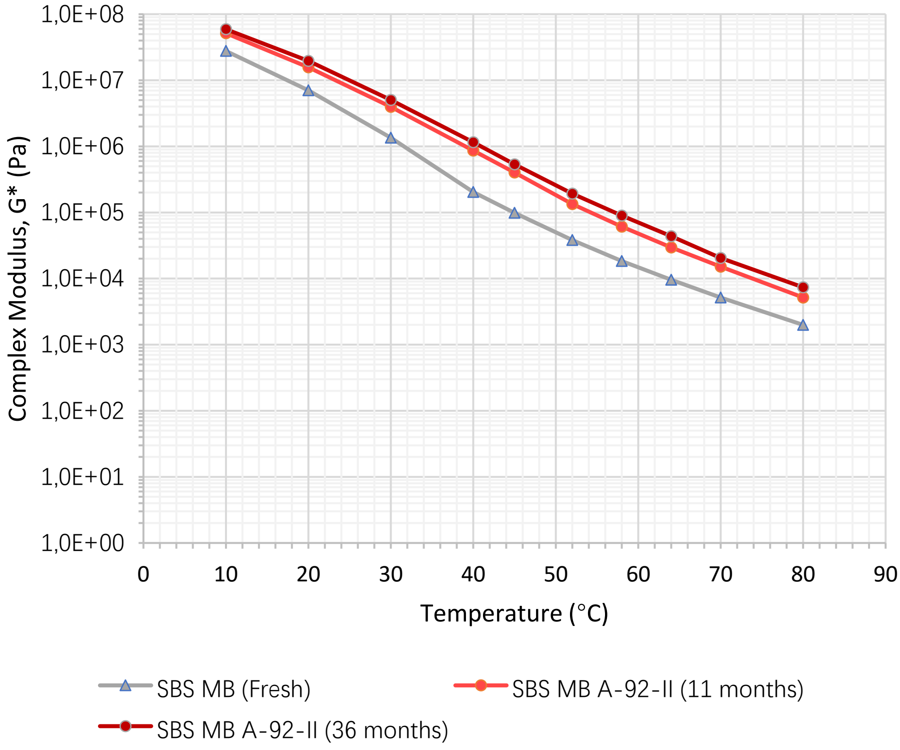

**Figure 4.1.20.** Isochrone curves at 5 Hz of the complex modulus of the SBSMB used in the A-92-II at different service-life periods.

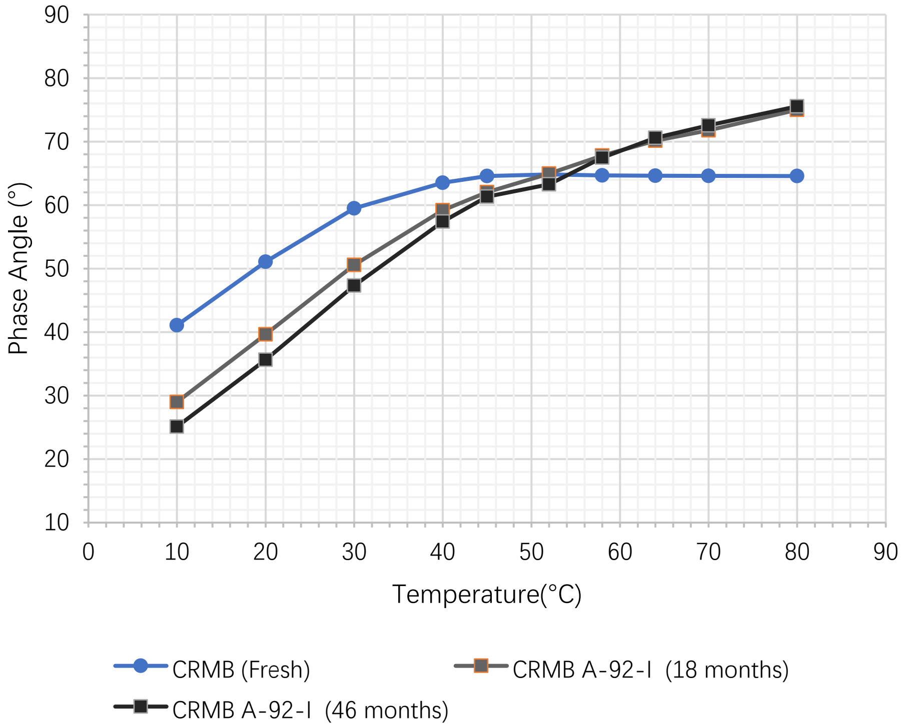

**Figure 4.1.21.** Isochrone curves at 5 Hz of the phase angle of the CRMB used in the A-92-I at different service-life periods.

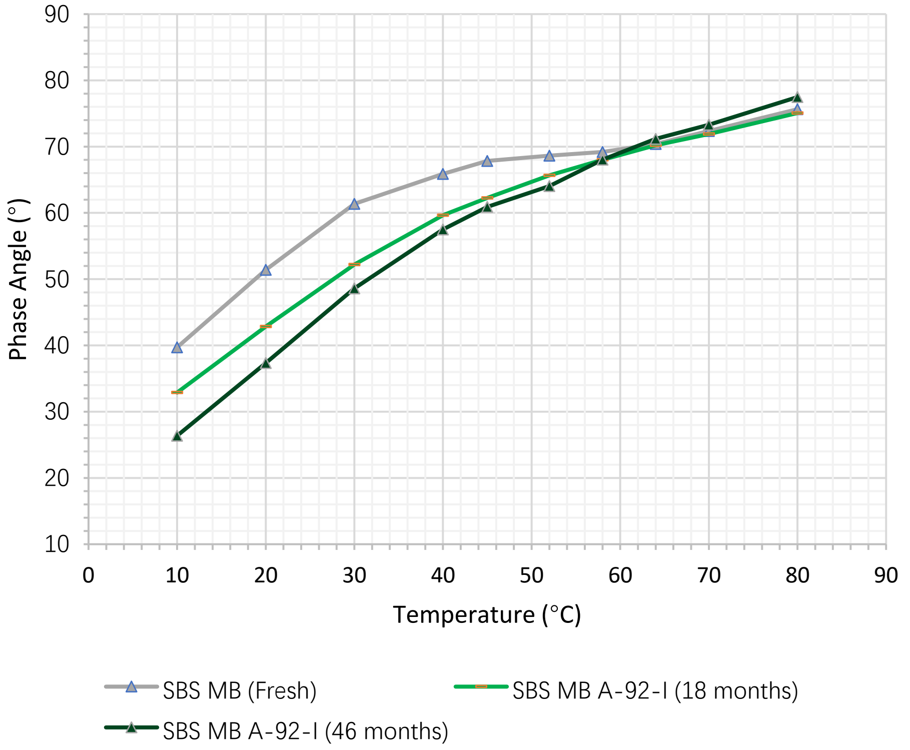

**Figure 4.1.22.** Isochrone curves at 5 Hz of the phase angle of the SBSMB used in the A-92-I at different service-life periods.

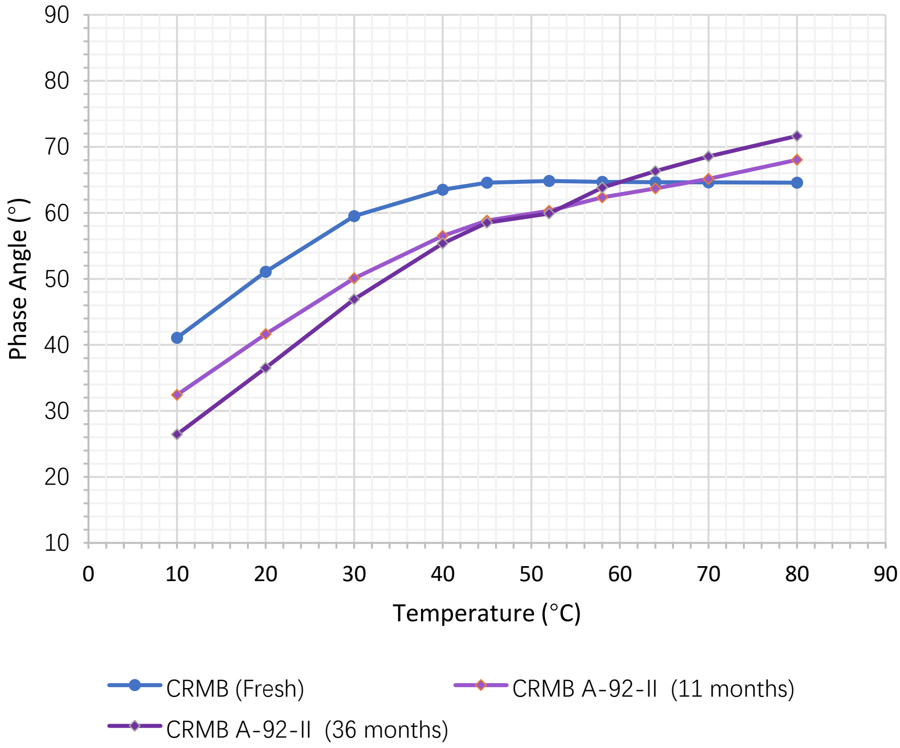

**Figure 4.1.23.** Isochrone curves at 5 Hz of the phase angle of the CRMB used in the A-92-II at different service-life periods.

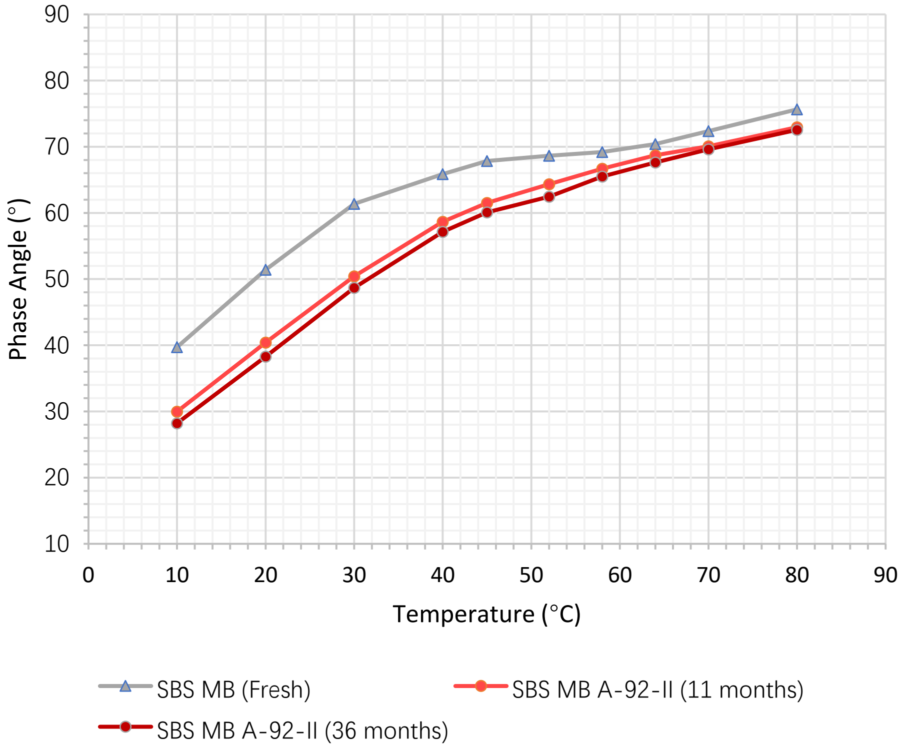

**Figure 4.1.24.** Isochrone curves at 5 Hz of the phase angle of the SBSMB used in the A-92-II at different service-life periods.

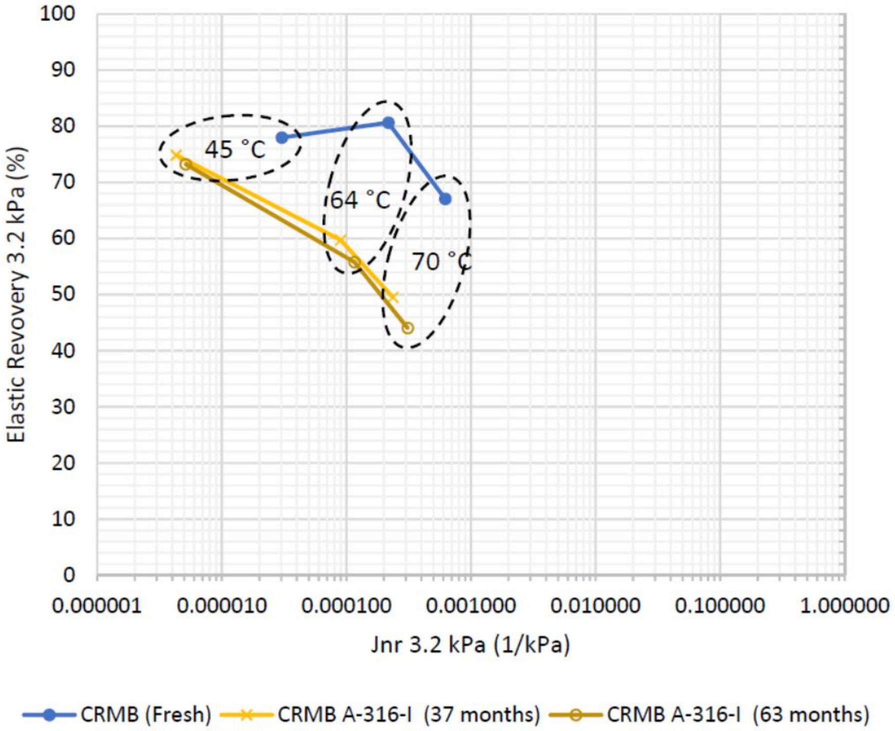

**Figure 4.1.25.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the CRMB used in the A-316-I at different service-life periods.

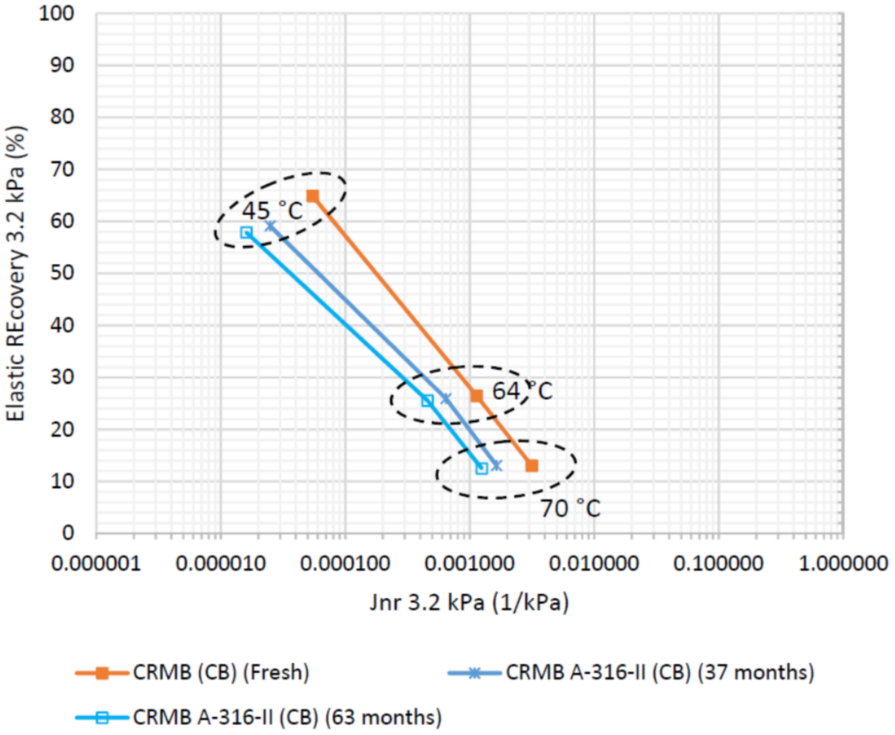

**Figure 4.1.26.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the CRMB (CB) used in the A-316-II at different service-life periods.

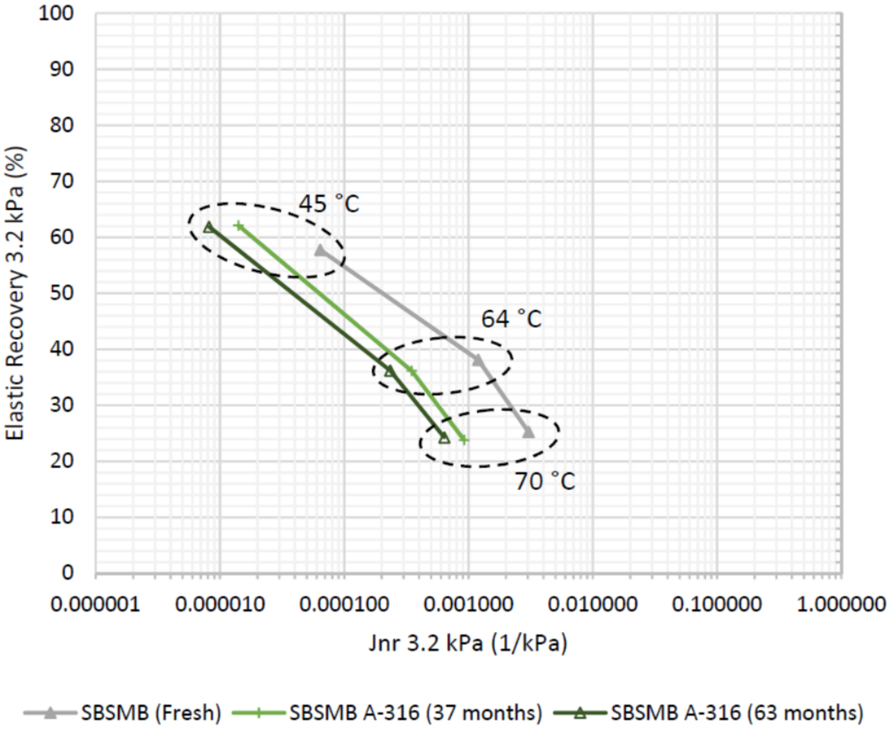

**Figure 4.1.27.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the SBSMB used in the A-316 at different service-life periods.

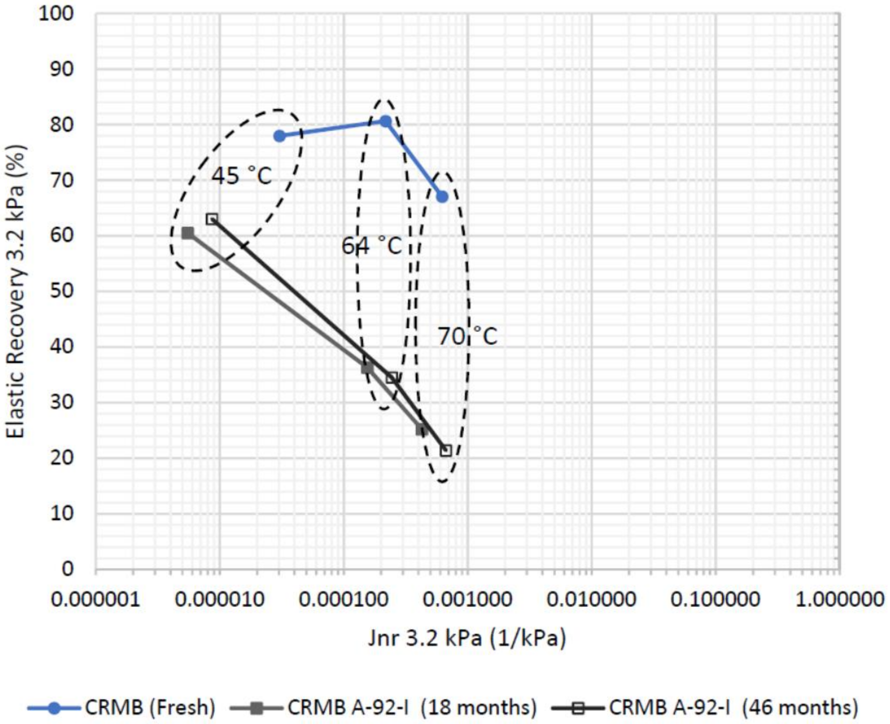

**Figure 4.1.28.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the CRMB used in the A-92-I at different service- life periods.

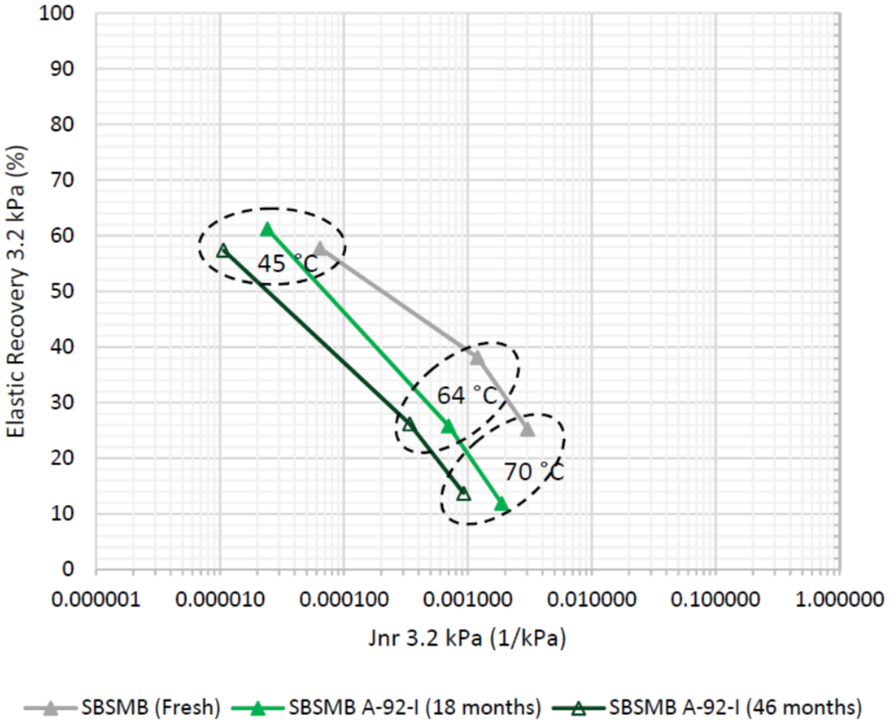

**Figure 4.1.29.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the SBSMB used in the A-92-I at different service-life periods.

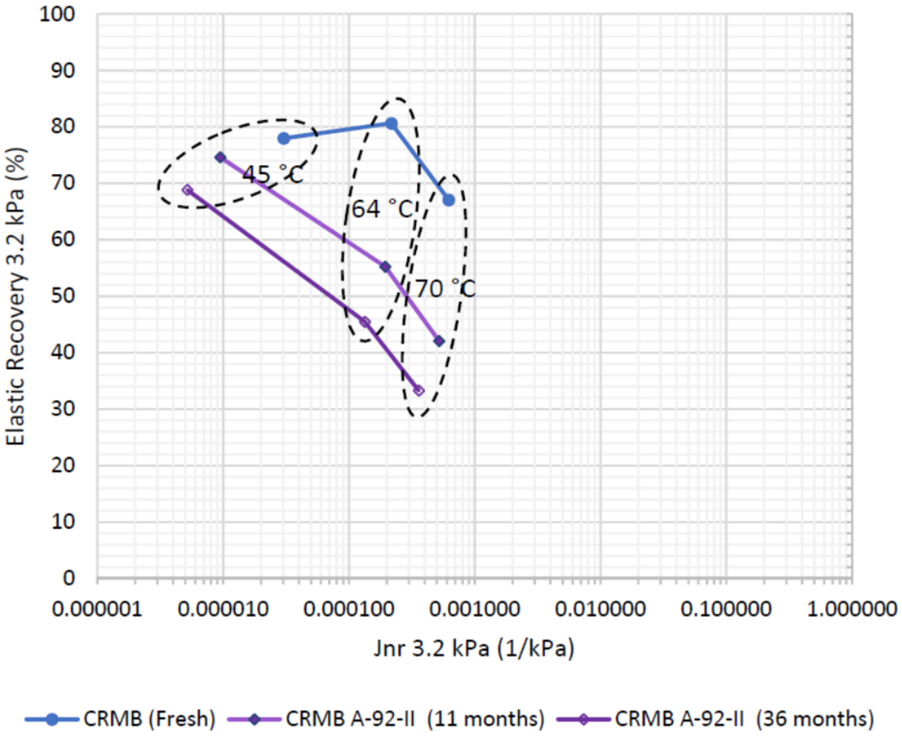

**Figure 4.1.30.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the CRMB used in the A-92-II at different service-life periods.

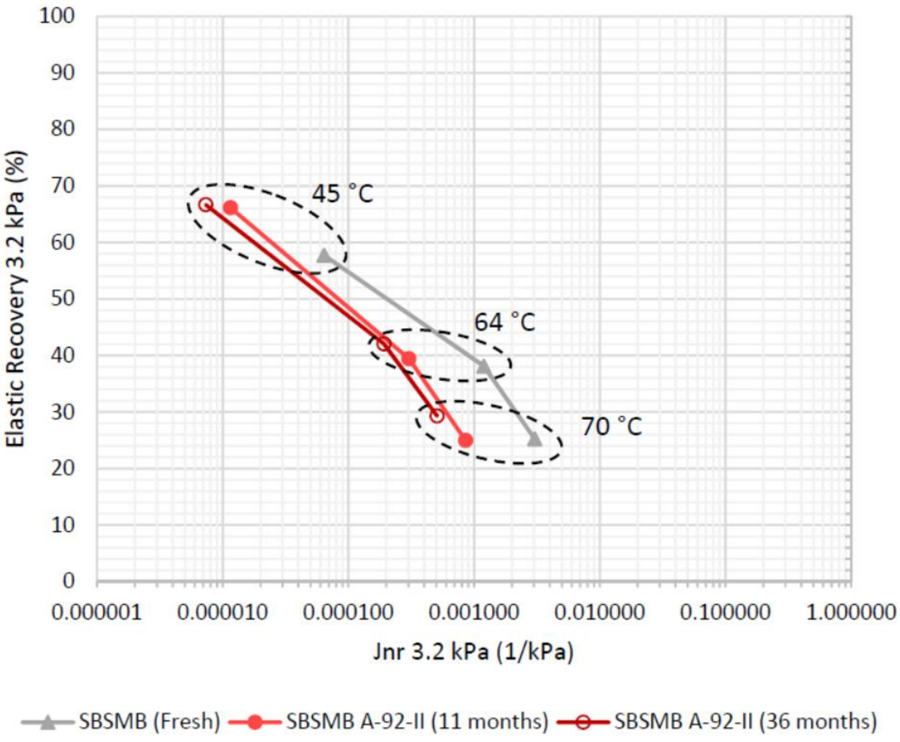

**Figure 4.1.31.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the SBSMB used in the A-92-II at different service-life periods.

The analysis of the evolution of the rheological properties of the binders, studied as a function of the service life, through the L-Index and T-Index parameters, demonstrated that all materials became less susceptible to mechanical loads over time (lower values of L-Index). This may be associated with the stiffening process (Figure 4.1.32). Similarly, all SBSMB and CRMB (CB) became less susceptible to thermal gradients as the service life progressed (lower values of T-Index). However, this property seemed to remain unaffected in the CRMB mixture (Figure 4.1.33).

As a general conclusion, it can be stated that regardless of the scenario studied, the three binders evaluated were found to have similar evolutions of their rheological properties as a function of the service life. Figures 4.1.34 and 4.1.35 analyse the L-Index and T-Index of the binders studied overall, regardless of the highway section. These figures demonstrate that none of the binders was found to have excessive deterioration with respect to the others. Moreover, it has been observed that the ageing produced during the service life renders the binder less susceptible to mechanical loads and to thermal effects, which means that ageing leads to binders of a more stable nature.

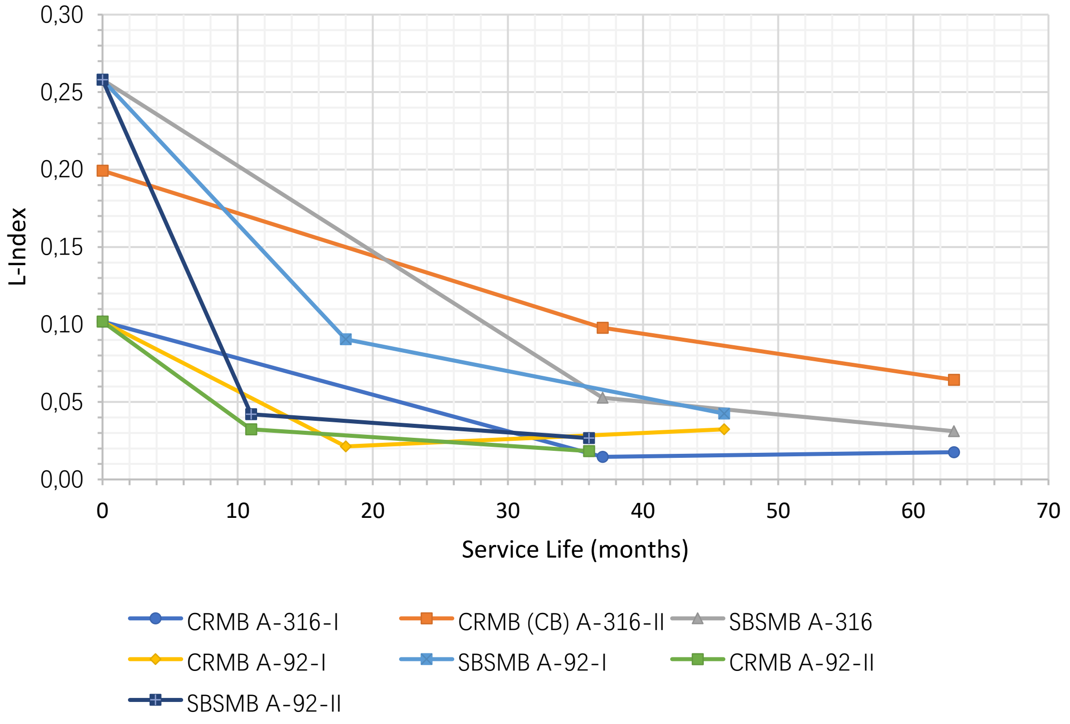

**Figure 4.1.32.** Evolution of L-Index as a function of the service life for the different asphalt binders and highway sections studied.

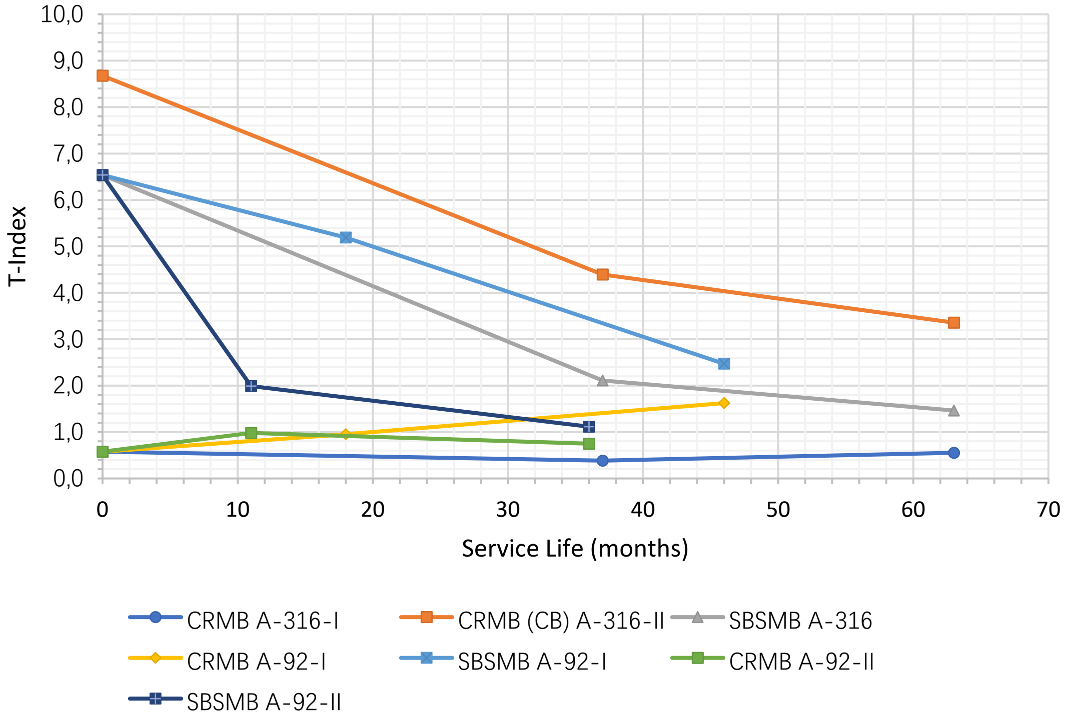

**Figure 4.1.33.** Evolution of T-Index as a function of the service life for the different asphalt binders and highway sections studied.

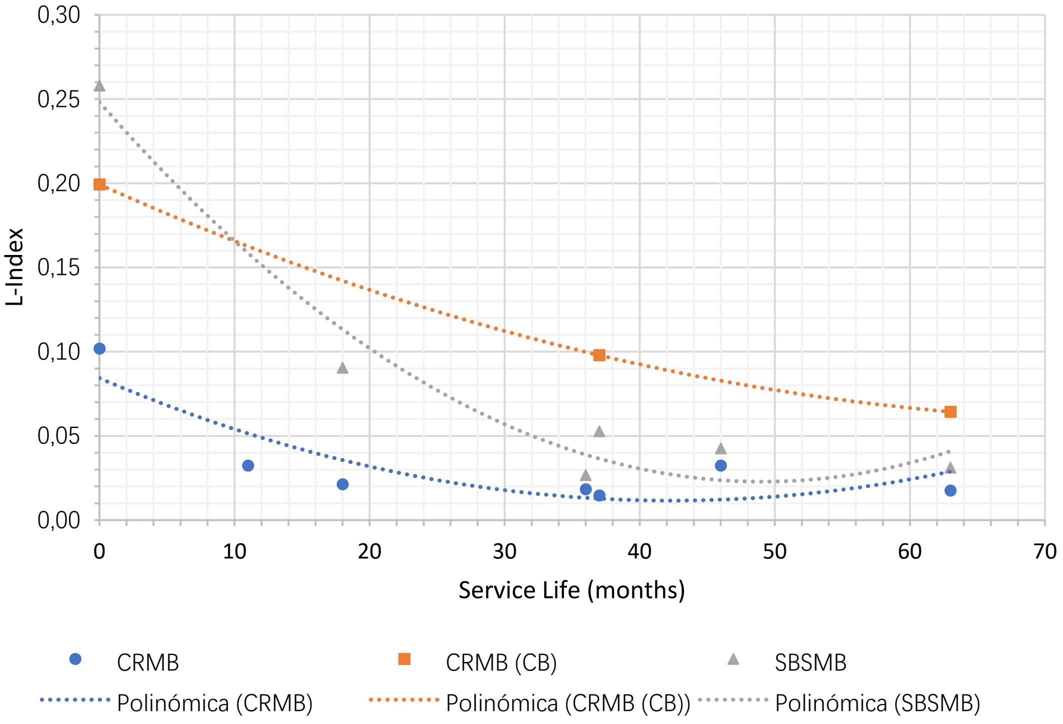

**Figure 4.1.34.** Evolution of L-Index as a function of the service life for the different asphalt binders studied.

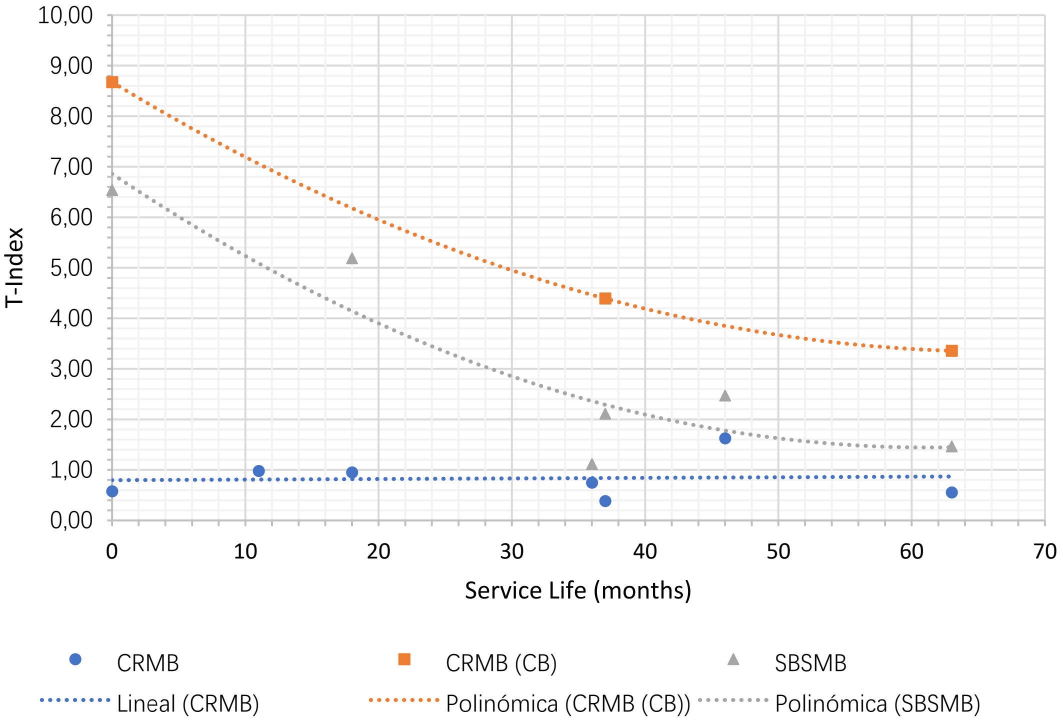

**Figure 4.1.35.** Evolution of T-Index as a function of the service life for the different asphalt binders studied.

### 4.1.5. Conclusions.

This paper summarises the results obtained in the present research study, whose main objective is to carry out an in-depth analysis of the rheological properties of crumb rubber modified bitumen under real traffic and climate conditions. For this purpose, cores were extracted at different dates from the surface layers of several highway sections in Andalusia, Spain. The binder from these cores was then recovered, tested in the laboratory, and compared to the properties of the same binder prior to production. From the results obtained in this study, the following conclusions may be drawn:

For ageing under real service conditions, the three modified binders studied (CRMB, CRMB (CB) and SBSMB) were found to present an increase in their complex modulus at all test temperatures studied after in-service ageing, but the CRMB and CRMB (CB) were found to have an increase in phase angle at high temperatures, which was unexpected according to previous results obtained at laboratory level. This inferred that the binders became less elastic in such an environment and that the positive effect of the recycled polymers added was lost at that temperature since, at lower temperatures, the expected reduction in their phase angle was found. The SBSMB was not found to have these phase angle values at high temperatures after ageing on the highway, which demonstrated that this material had lower susceptibility to harsh traffic and climatic actions.

Despite the different degrees of deterioration found for the three binders subsequent to testing, they all demonstrated that such differences were minor when their performances were compared. Thus, by ensuring the high-performance properties of the binders prior to manufacturing an asphalt mixture, a sufficient indicator may be provided for constructors and agencies that the binder will have an appropriate long-term performance, regardless of the harshness of the service conditions.

No significant differences were found between the CRMB and CRMB (CB) after ageing, which suggested that both binders were similarly affected by the highway service conditions. In this respect, it may also be concluded that CRMB could offer similar service conditions to those of SBSMB, despite their elastic performance at higher temperatures.

The results obtained in the present study show that, under real severe traffic and climate conditions, the crumb rubber modified bitumen presents similar characteristics subsequent to ageing to those offered by asphalt mixtures manufactured with traditional SBS modified bitumen. Nonetheless, the time period analysed in this study (63 months) remains distant from the threshold established for this type of material, and it is therefore of interest to continue this study into the future.

### 4.1.6. References.

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## 4.2. Analysis of the Real Performance of Crumb-Rubber-Modified Asphalt Mixtures.

Este capítulo está basado en la siguiente publicación: Francisco Javier Sierra-Carrillo del Albornoz, Fernando Moreno-Navarro and María del Carmen Rubio-Gámez; **Analysis of the Real Performance of Crumb-Rubber-Modified Asphalt Mixtures**. *Materials 2022, 15, 8366. https://doi.org/10.3390/ma15238366*.

### 4.2.1. Abstract.

The main goal of this study is to evaluate the field performance of crumb-rubber-modified asphalt mixtures used as a surface layer on high-volume traffic roads. For this purpose, several road sections were constructed under different climate conditions and using control mixtures (manufactured with traditional SBS polymer-modified binders) and crumb-rubber-modified mixtures. After the construction of the different road sections, cores were taken at different periods of their service life (up to 63 months) and they were tested in the laboratory in order to assess the evolution of the density, stiffness and fatigue resistance of the layers. Based on the results obtained from tests, it can be concluded that under real severe traffic and climate conditions, asphalt mixtures manufactured with crumb-rubber-modified bitumen offer ageing and mechanical performance very similar to that offered by asphalt mixtures manufactured with traditional SBS-modified bitumen. Based on these considerations, this application can be an interesting solution to minimize environmental problems caused by end-of-life tires in landfills.

### 4.2.2. Introduction.

End-of-life tires are one of the most widely produced types of solid waste around the world [1]. They are composed of high-quality materials such as rubber, metallic fibers, nylon fiber, etc., that are difficult to degrade but which can offer interesting solutions to primary materials when they are re-used for a second purpose. Therefore, during the last few decades, many efforts have been made to find applications for the valorization of end-of-life tires [2–6]. One of the most common and successful applications is to reuse their rubber as a binder modifier in bituminous mixtures. For this purpose, the rubber from the tire is transformed into crumb, and it is incorporated into the asphalt binder (wet process) or directly into the mixture as a part of the mineral skeleton (dry process) [7].

Its application as a modifier in bituminous mixtures permits the recovery of this waste in huge quantities, helping to contribute to circular economy principles (around 1000 tires could be reused per kilometer of road, when using a bituminous mixture modified with 0.5% of its total weight and a thickness layer of 6 cm). In addition, many laboratory studies have demonstrated that the use of crumb rubber as a modifier of asphalt mixtures improves their resistance to fatigue cracking [8,9] and to plastic deformation [10], reduces their ageing [11], increases their durability [12,13] or minimizes the rolling noise [14,15]. Thus, this method of valorization can result in more durable road pavements, with less need for maintenance, which contributes to the more sustainable and effective management of natural, economic and energy resources.

After decades of use, there are many experiences that have already proven the advantages of the application of crumb rubber from end-of-life tires as a bituminous mixture modifier [16–24]. However, in other countries, such as Spain [25,26], there are doubts about the efficiency in the long term, especially when they are applied on surface layers, on high-volume traffic roads or in severe climate conditions. Traditionally, the performance of the applications has not been properly documented and there is a lack of information, which prevents road administrators from selecting these materials instead of traditional SBS-modified binders (which have decades of success and trustable use). Therefore, the application of crumb rubber is not common under these circumstances. In addition, there is some skepticism about its workability in cold climates [27], its stability to form an homogeneous blend [8] or its skid resistance [28], as well as about its economic and environmental viability [29].

In order to determine in depth the real performance of crumb-rubber-modified asphalt mixtures, during the last few years, the road administration of the government of Andalusia (Spain) has applied them on the surface layers of some highway sections that experience high volumes of traffic and unfavorable climate conditions. To evaluate these materials, a study on the evolution of the mechanical performance of them during their service life in comparison to traditional SBS-modified material has been carried out in collaboration with the Laboratory of Construction Engineering of the University of Granada. For this purpose, cores directly extracted from the surface layer of the pavement at different dates were tested at the laboratory, determining the evolution of important parameters such as density, stiffness or fatigue cracking resistance. This paper summarizes the main results obtained in this research work so far.

## 4.2.3. Materials and Methods.

### *4.2.3.1. Materials.*

This paper is focused on the study of 3 sections of the high-traffic-capacity road network of Andalusia (Spain), on the A-316 highway (Jaen) and A-92 highway (Granada, in two different locations). The main characteristics of these highway sections are summarized in Table 4.2.1. The A-316 offered less severe service conditions, with less than 600 heavy vehicles daily and no presence of snow/ice over the road surface. On the opposite site, the A-92-I offered the most severe conditions in terms of traffic and climate (more than 3000 heavy vehicles pass every day and the presence of snow, frost and chemical substances for de-icing is quite common for 5 months every year).

**Table 4.2.1.** Characteristics of the service conditions in the sections studied.

| | **A-316** | **A-92-I** | **A-92–II** |
|---|---|---|---|
| Date of traffic opening | November, 2015 | September, 2017 | July, 2018 |
| Annual average daily traffic (Number of vehicles) | 8000 | 18,000 | 11,000 |
| Percentage of heavy traffic (over the total number of vehicles) | 8 | 17 | 7 |
| Climate conditions | ~750 m above sea level; rarely frost/snow over the road surface during autumn/winter; maximum average temperatures in summer ~36 °C; minimum average temperatures in winter ~4 °C | ~1400 m above sea level; very frequent frost/snow over the road surface during autumn/winter; maximum average temperatures in summer ~30 °C; minimum average temperatures in winter ~1 °C | ~1100 m above sea level; frequent frost/snow over the road surface during autumn/winter; maximum average temperatures in summer ~33 °C; minimum average temperatures in winter ~4 °C |

All these sections were constructed using a surface layer of 3 cm thickness and using different job mix formulas of BBTM 11B PMB 45/80-60 C (an asphalt mixture composed of a gap-graded mineral skeleton with a maximum aggregate size of 11 mm and manufactured with a crumb-rubber-modified asphalt binder [30]). In all the highway sections studied, a sub-section of around 400 m was also constructed using BBTM 11B PMB 45/80-60, manufactured with the same mineral skeleton but using a conventional SBS polymer-modified bitumen from a refinery (these reference sections were constructed side by side to ensure the same environmental and traffic conditions as the crumb-rubber-modified asphalt layers). Table 4.2.2 summarizes the main characteristics of the job mix formulas used in the construction of the different sections studied. As can be observed, all the job mix formulas offered similar properties (optimal binder content, density and voids) and mechanical performance, measured in laboratory tests conducted on mixture samples obtained in the asphalt plants used during the construction of the highway sections studied. In addition, it must be highlighted that there were no significant differences between them in terms of costs, workability or bitumen homogeneity.

**Table 4.2.2.** Characteristics of the job mix formulas used in the construction of the highway sections studied.

| | **SBS A-316** | **CR A-316 (I)** | **CR A-316 (II)** | **SBS A-92** | **CR A-92** |
|---|---|---|---|---|---|
| Type of aggregate coarse fraction (6/12 mm) | Ophite | Trachyte | Ophite | Ophite | Ophite |
| Type of aggregate fine fraction (0/6 mm) | Siliceous | Limestone | Siliceous | Limestone | Limestone |
| Type of filler | Portland Cement | Portland Cement | Portland Cement | Portland Cement | Portland Cement |
| Type of binder | SBS PMB 45/80-60 | CR PMB 45/80-60 Continuous blend (CB) | CR PMB 45/80-60 Terminal blend (TB) | SBS PMB 45/80-60 | CR PMB 45/80-60 Terminal blend (TB) |
| Optimal binder content (%/mixture weight) | 4.78 | 4.79 | 4.82 | 4.80 | 4.75 |
| Aparent density (g/cm$^3$), UNE-EN 12697-6 [31] | 2.386 | 2.087 | 2.391 | 2.146 | 2.178 |
| Voids in mixture (%), UNE-EN 12697-8 [32] | 14.3 | 16.9 | 15.1 | 16.5 | 18.0 |
| Dry indirect tensile strength (kPa) [33] | 1702 | 1670 | 1691 | 1287 | 1100 |
| Indirect tensile strength ratio (%) [34] | 88.9 | 94.8 | 84.3 | 91.9 | 95.5 |
| Wheel tracking slope (mm/10$^3$ cycles) [35] | 0.06 | 0.04 | 0.08 | 0.06 | 0.05 |

Figure 4.2.1 shows the rheological properties (black diagrams) of the fresh binders used in the manufacture of the mixtures.

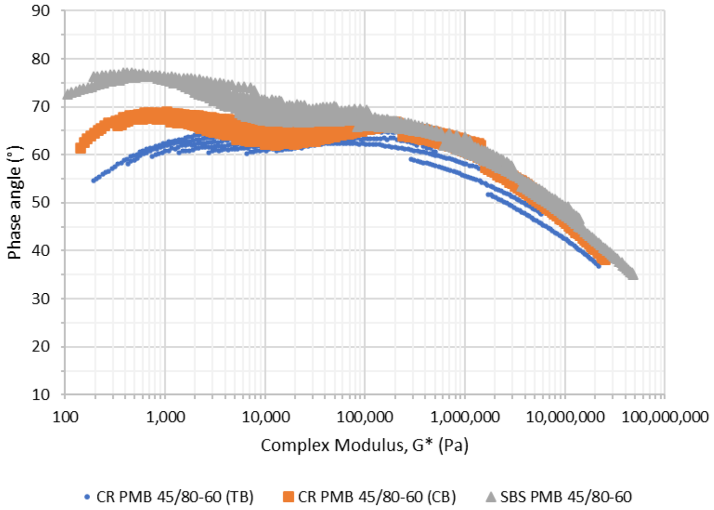

**Figure 4.2.1.** Rheological performance of the binders used in the manufacture of the mixtures.

### *4.2.3.2. Testing Plan.*

During the service life of the three highway sections studied, cores from the Surface layers were extracted at different times (Table 4.2.3). A total of 6 cores on each extraction campaign were obtained from the different mixtures studied. All these cores were obtained in the right carriageway over the wheel path at the same 6 different kilometric points in order to avoid the inclusion of new variables in the study (Figure 4.2.2). Once the cores were extracted, the 3 cm surface layers were sawed at the laboratory to be tested.

**Table 4.2.3.** Dates on which the cores were extracted in each highway section studied.

| Core Extraction Campaign | A-316 | A-92-I | A-92-II |
|---|---|---|---|
| 1 | 0 months (November, 2015) | 1 month (October, 2017) | 11 months (June 2019) |
| 2 | 6 months (May, 2015) | 18 months (March, 2019) | 36 months (July 2021) |
| 3 | 37 months (January, 2019) | 46 months (July, 2021) | - |
| 4 | 63 months (February, 2021) | - | - |

**Figure 4.2.2.** Details of the core extraction process

The superficial aspects of the highway sections studied during the last campaign are shown in Figures 4.2.3-4.2.5.

**Figure 4.2.3.** Aspects of the surface asphalt layers manufactured with SBS and crumb-rubber-modified binders on A-316 highway after 63 months of service life.

**Figure 4.2.4.** Aspects of the surface asphalt layers manufactured with SBS and crumb-rubber-modified binders on A-92 highway after 46 months of service life.

**Figure 4.2.5.** Aspects of the surface asphalt layers manufactured with SBS and crumb-rubber-modified binders on A-92 highway after 36 months of service life.

Once the cylindrical cores were obtained from the road on the different dates, their apparent density (according to UNE-EN 12697-6 [31] for specimens with more than 10% of voids in mixture) was determined using the geometric procedure (where the mass of the core is divided by the volume of the core defined by their height and diameter). After this, their stiffness at 20 °C was measured according to UNE-EN 12697-26 (annex C) [36], where 15 indirect tensile load pulses (10 of conditioning, and the last 5 used for measured the average stiffness of the core), in the form of versine and with a 3 s duration for each one, were applied in two different diameters of the core (the value of stiffness is considered as the average of the average values obtained in the last 5 load pulses of each diameter). After this, the fatigue cracking resistance of the cores was measured using the University of Granada-Fatigue Asphalt Cracking Test (UGR-FACT) [37]. The configuration of the testing device [38] induced combined efforts in the cores (bending, tensile and shear), similar to those that occurred during their service life in the pavement layer (Figure 4.2.6). Based on the displacements measured and on the number of load cycles required to produce their failure (the total propagation of a crack causing the breakage of the specimen into two pieces), the fatigue resistance of the materials was obtained. This test was demonstrated to be a useful and sensitive tool to measure the influence of different design parameters, such as the aggregate nature [39], the type of binder [40–42], the use of additives [43] or the traffic and climatic service conditions [44,45], on the fatigue and structural resistance of asphalt mixtures. In addition, UGR-FACT was already demonstrated to be a good tool for studying the effect of sustainable technologies on asphalt materials' cracking resistance, such as healing [46], different warm-mix asphalt technologies [47] or the addition of crumb rubber [9]. During this research, the cores obtained on different dates in the three highway sections were tested using versine load cycles of 0.2 MPa amplitude at a frequency of 5 Hz at 15 ºC. For this purpose, they were sawed to obtain specimens with 100 mm máximum length, 60 mm maximum width and 30 mm thickness (Figure 4.2.6).

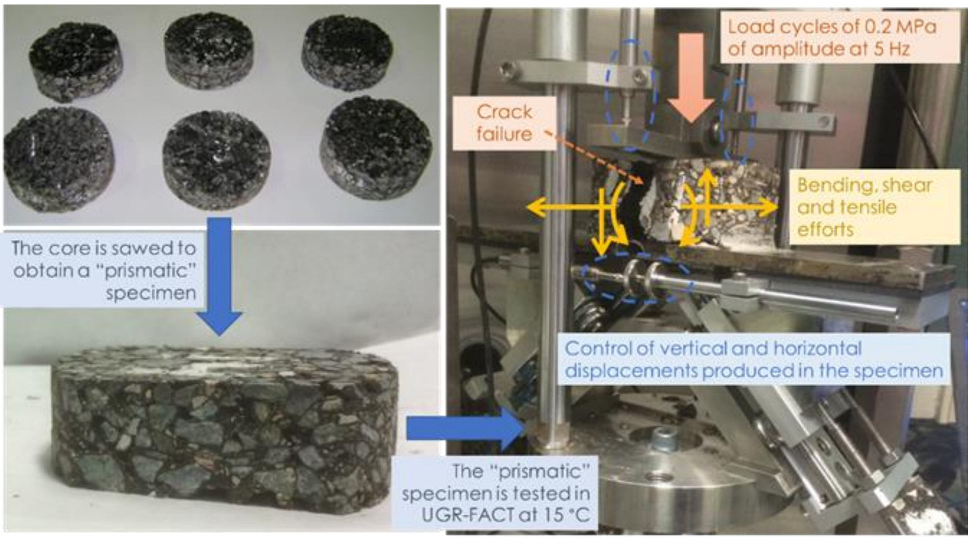

**Figure 4.2.6.** Schema of the UGR-FACT method.

## 4.2.4. Analysis of Results.

Figure 4.2.7 shows the evolution of the cores' densities as a function of the service life, for each section of highway studied. As can be observed, slight variations were observed in terms of density of the asphalt layers along their service life (thus, the changes observed in their mechanical performance cannot be related to this parameter). In addition, it can be said that no differences were observed between the mixtures manufactured with the crumb-rubber-modified bitumen and those using the SBS-modified one (the evolution of the density of the layers is the same regardless the type of modified binder used). Furthermore, the binder content measured in the cores and their aggregate gradations were also very constant along the service life.

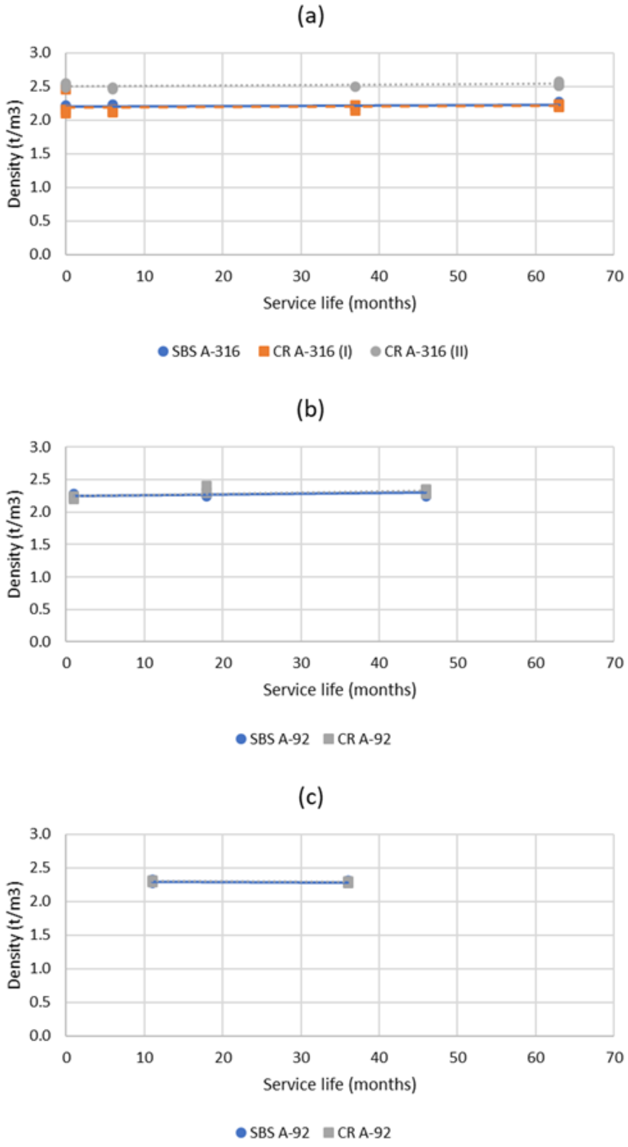

**Figure 4.2.7.** Evolution of the densities measured in the cores obtained along the service life of the highway sections studied: (a) A-316; (b) A-92-I; (c) A-92-II.

The evolution of the stiffness of the layers as a function of the service life is shown in Figure 4.2.8. It is observed that, due to ageing, the asphalt layers increased in stiffness linearly along their service life, regardless of the type of bituminous binder used (it must be highlighted the high correlation coefficient of the straight line). SBS polymer-modified asphalt mixtures had a rate of stiffness increment of around 64 MPa/month in the A-316 section, 49 MPa/month in the A-92-I section and 67 MPa/month in the A-92-II section (which gives an average of 60 MPa/month, with a coefficient of variation of 15%). Refinery crumb-rubber-modified asphalt mixtures (terminal blend) had a rate of stiffness increment of 58 MPa/month in the A-316 section, 78 MPa/month in the A-92-I section and 105 MPa/month in the A-92-II section (which gives an average of 80 MPa/month, with a coefficient of variation of 30%). Based on these results, it can be said that no significant differences were found between highway sections and that the crumb-rubber-modified asphalt binder suffered a 25% higher stiffness variation than the SBS-modified one. Nonetheless, when analyzing the mixture manufactured with the continuous-blend crumb-rubber-modified bitumen in the A-316 section, it was observed that the rate of stiffness increment was 43 MPa/month, which was 30% less than the stiffness increment observed in the SBS-modified one for the same circumstances. Therefore, it can be concluded that crumb-rubber-modified bitumens and SBS-modified bitumens offer stiffness effects in a similar order during their service life.

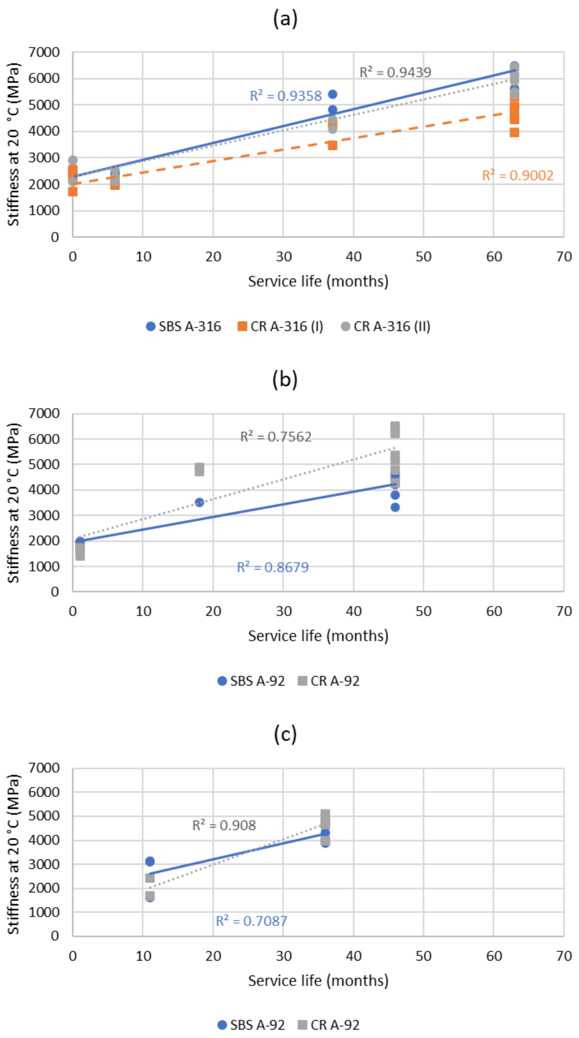

**Figure 4.2.8.** Evolution of the stiffness measured in the cores obtained along the service life of the highway sections studied: (a) A-316; (b) A-92-I; (c) A-92-II.

Figure 4.2.9 shows the fatigue laws obtained from the cores extracted at different periods of the service life of the highway section studied using UGR-FACT. As can be observed, there were no significant differences between the mixtures manufactured with the crum-brubber- modified binders and the SBS-modified ones (for the same job mix formula, no significant differences have been obtained). Instead, it is shown that the BBTM 11B job mix formula used in A-92 offered slightly higher fatigue resistance than those used in A-316. Thus, it can be said that crumb-rubber-modified asphalt binders also offer similar long-term performance under cycling fatigue loads as the SBS-modified bitumens.

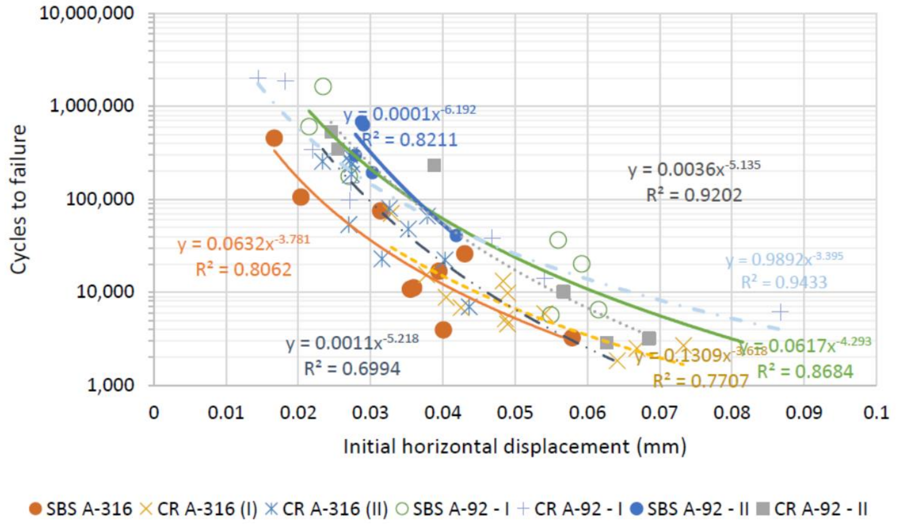

**Figure 4.2.9.** Fatigue laws measured in the cores obtained along the service life of the highway sections studied.

Figure 4.2.10 shows the evolution of the fatigue cracking resistance of the asphalt layers studied as a function of the service life in A-316 and A-92 sections, measured using UGR-FACT. Due to the similarity in the fatigue laws obtained, the results were grouped in order to show the trend marked by the service life. In this respect, it was observed that the fatigue resistance of asphalt layers tends to increase during the first periods of their service life (until 20–40 months, depending on the traffic volume and due to the strain hardening suffered [9]), and after this, it starts to decrease, which marks a point at which the traffic loads would start to deteriorate the asphalt layer.

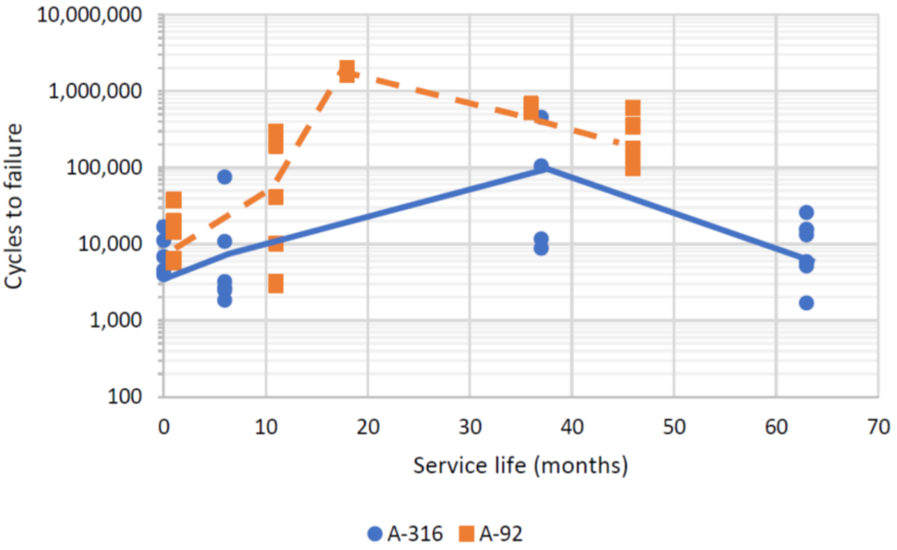

**Figure 4.2.10.** Evolution of the resistance to fatigue cracking of the highway section studied as a function of the service life.

### 4.2.5. Conclusions.

This paper summarizes the results obtained in a research study whose main objective was to carry out an in-depth analysis of the mechanical performance of crumb-rubber modified bitumen under severe traffic and climate conditions in real road pavements. For this purpose, cores were extracted on different dates from the surface layers of three highway sections that were constructed using a crumb-rubber-modified bitumen (PMB 45/80-60 C), and they were compared with cores extracted on the same date and at the same location from surface layers constructed with SBS-modified bitumen (PMB 45/80-60). These cores were tested at the laboratory to determine their density (UNE-EN 12697-6), stiffness (UNE-EN 12697-26, annex C) and resistance to fatigue (UGR-FACT). From the results obtained in this study, the following conclusions can be drawn:

- The density of the surface layers studied was not affected by the service life (being constant over time and very similar to those reached after the pavement's construction), regardless of the type of asphalt binder used (SBS or crumb-rubber-modified).

- The stiffness of the surface layers studied was significantly affected by the service life due to the effects of the environmental agents. The mixture BBTM 11B showed a rate of stiffness increment between 43 and 105 MPa per month, but we did not observe a clear dependence of this rate on the type of binder used or the climate conditions in the highway section studied. Thus, it can be concluded that surface asphalt mixtures manufactured with SBS or crumb-rubber-modified binders offer a similar stiffening process during their service life.

- The results obtained in terms of long-term resistance (fatigue cracking) also demonstrated that the mixtures manufactured with SBS or crumb-rubber-modified binders offer similar performance. In both types of materials and in the three highway sections studied, it was observed that during the first 20–40 months of service life (depending on the volume of traffic supported), the surface asphalt mixtures increased in resistance to fatigue loading (due to the strain hardening phenomenon), and after this period, they became susceptible to fatigue damage (which, in the end, would cause the failure of the layer).

The results obtained in the study presented show that, under real severe traffic and climate conditions, the asphalt mixtures manufactured with crumb-rubber-modified bitumen offer ageing and mechanical performance very similar to that offered by asphalt mixtures manufactured with traditional high-performance SBS-modified bitumen. As future research, it would be interesting to continue this study by adding aspects related to the serviceability of pavements and road safety, such as IRI or skid resistance, and applying a life cycle cost analysis to determine the materials' real efficiency.

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## 4.3. High-Performance Sustainable Asphalt Mixtures for High-Volume Traffic Roads in Severe Climates.

Este capítulo está basado en la siguiente publicación: Fernando Moreno-Navarro, Francisco Javier Sierra, Miguel Sol-Sánchez, María del Carmen Rubio-Gámez, Manuel Castillo and Eugenio Estévez; **High-Performance Sustainable Asphalt Mixtures for High-Volume Traffic Roads in Severe Climates**. *Sustainability 2020, 12, 8765; doi:10.3390/su12218765*

### 4.3.1. Abstract.

This paper summarizes the work carried out in a research project whose main objective was to develop high-performance sustainable bituminous materials (using crumb rubber and additives to reduce their manufacturing temperature) to be used in roads that support high traffic volumes and/or severe environmental conditions. For this purpose, various studies were conducted both in a laboratory and in a real asphalt plant (at binder and mixture level). Later, these materials were used to construct a trial section in a highway at a mountain pass (at more than 1400 m above sea level) supporting more than 3000 heavy vehicles each day under severe environmental conditions (snow during winter, and high temperatures and many hours of solar radiation during the summer). The results indicate the viability of using these materials, since they provide a number of advantages such as improved workability at lower temperatures and an increase in the mechanical resistance against the main sources of distress that affect asphalt pavements.

### 4.3.2. Introduction.

The economic and social developments of recent decades have led to the need for more efficient and sustainable road infrastructures. In this regard, efforts have been focused on developing more durable materials that allow for increasing the service life of road pavements (by, for instance, optimizing economic investment while minimizing the social impact by reducing traffic interruption and pollution) [1]. Similarly, more sustainable products and construction processes are being developed to minimize the consumption of raw materials and energy while reducing the pollution that is generated during construction, maintenance, or renewal activities. Thus, one of the current challenges in the road pavement industry concerns the implementation of a circular economy in which materials are reused whilst applying more environmentally friendly construction techniques [2–4].

Given these current challenges, the use of crumb rubber as a binder modifier is becoming an increasingly widespread solution due to the environmental benefits of reducing the accumulation of this waste material, along with the fact that this modifier appears to provide the binder with a higher viscosity than conventional polymers (such as

SBS and EVA) [5]. This allows for the use of higher dosages of bitumen during the manufacturing of asphalt mixtures, which in turn results in greater resistance to cracking [6,7], whilst also reducing permanent deformations, binder aging, and susceptibility to in-service temperature fluctuations [8,9].

However, despite these benefits, an increase in binder viscosity limits the workability of the asphalt mixtures (since they require a higher manufacturing temperature and more compaction energy whilst being more susceptible to lower temperatures during pavement construction) [10]. All of this implies a greater risk when applying these materials in cold climates or in situations that involve long transport distances. Thus, applying mixtures with crumb rubber could be limited under these circumstances, while negative economic and environmental impacts can also be seen in other cases due to the need for a higher manufacturing temperature.

In order to address this issue, a joint research project carried out by the Ministry of Public Works and Housing of Andalucía (Junta de Andalucía), the construction company Pérez Jiménez, and the Laboratory of Construction Engineering of the University of Granada, has focused on developing a high-performance sustainable asphalt mixture manufactured with crumb rubber from end-of-use tires at a low temperature (by using additives to obtain warm mix asphalts) [11–13]. The aim of this project was to obtain a material that could be used as an overlay in the rehabilitation of a road subjected to a high volume of traffic and/or severe climate conditions. This paper presents the main findings from the laboratory phase of developing this mixture (binder and mixture level), its production in-plant, and its application in the rehabilitation of a pavement section in the A-92 Highway (in the province of Granada, Spain).

## 4.3.3. Methodology.

### *4.3.3.1. Materials.*

Given the need to obtain a high-performance and sustainable asphalt mixture (for the rehabilitation of deteriorated road pavements to improve safety and comfort), the type of mixture selected for this study was a BBTM 11 [14]. This material has a high air void content (12–18%) and is commonly used as a surface layer with a thickness of around 3–4 cm, providing a significant reduction in noise while increasing vehicle-road adherence and reducing water splash.

For the design of this mixture, limestone aggregates were used for the fine fraction (0/6 mm), ophitic aggregates for the coarse fraction (4/12 mm), and cement as a filler (all these materials have appropriate characteristics for the manufacturing of asphalt mixtures according to the Spanish Standard PG-3 [15]). For the binders, two types of high-performance bitumens were used: a crumb rubber (CR)-modified bitumen (referred to in this article as CRMB) and a SBS polymer-modified bitumen (referred to as PMB) used as a reference to evaluate the effect of crumb rubber. The main characteristics of aggregates and binders used for the manufacture of the asphalt mixtures are summarized in Tables 4.3.1 and 4.3.2.

**Table 4.3.1.** Characteristics of the aggregates used in the manufacture of the asphalt mixtures.

| | | Coarse Aggregate (4/12 mm) Ophite | Fine Aggregate (0/6 mm) Limestone |
|---|---|---|---|
| | Sieve | % of material passing | % of material passing |
| **Particle granulometry, (UNE-EN 933-1)** | 11.2 | 96.5 | 100 |
| | 8 | 47.5 | 100 |
| | 4 | 7.5 | 82.2 |
| | 2 | 0.4 | 73.9 |
| | 0.5 | 0.3 | 31.9 |
| | 0.063 | 0.3 | 2.5 |
| **Sand equivalent, (UNE-EN 933-8)** | | - | 81 |
| **Percent of fractured face (UNE-EN 933-5)** | | 100% | - |
| **Flakiness index, (UNE-EN 933-3)** | | 20 | - |
| **Resistance to fragmentation (UNE-EN1097-2)** | | 14 | - |
| **Resistance to polishing (UNE 146130 annex D)** | | 0.51 | - |
| **Cleaning of coarse aggregate (UNE 146130 annex C)** | | 0.02% | - |
| **Relative density and absorption (EN 1097-6)** | Apparent relative density | 2.85 g/cm$^3$ | 2.80 g/cm$^3$ |
| | Absorption coefficient | 1.57 % | 0.77 % |

**Table 4.3.2.** Characteristics of the binders used in the manufacture of the asphalt mixtures.

| **Characteristics** | **CRMB** | **PMB** |
|---|---|---|
| Penetration at 25 $^{0}$C (dmm), EN 1426 [16] | 45–80 | 45–80 |
| Softening point ($^{0}$C), EN 1427 [17] | > 60 | > 60 |
| Elastic Recovery at 25 $^{0}$C (%), EN 13398 [18] | > 70 | > 70 |

Using these materials, two different hot mix asphalt BBTM 11 were designed: CRMB-HMA and PMB-HMA (manufactured at 175 °C with the same mineral skeleton and binder content, but using CRMB and PMB, respectively). Additionally, a third asphalt mixture was developed using the same mineral skeleton and the CRMB, but its manufacturing temperature was reduced to obtain warm-mix asphalt (CRMB-WMA). For this purpose, a chemical additive was used during the manufacturing of the CRMB-WMA (which modifies the surface of the aggregate on an alkyl surface that is more compatible with the asphalt binder and improves manufacturing, paving, and compacting processes). The mineral skeleton was composed of 76% of 4/12 mm ophitic coarse aggregates, 20% of 0/6 mm limestone sand, and 4% of Portland cement filler (Figure 4.3.1).

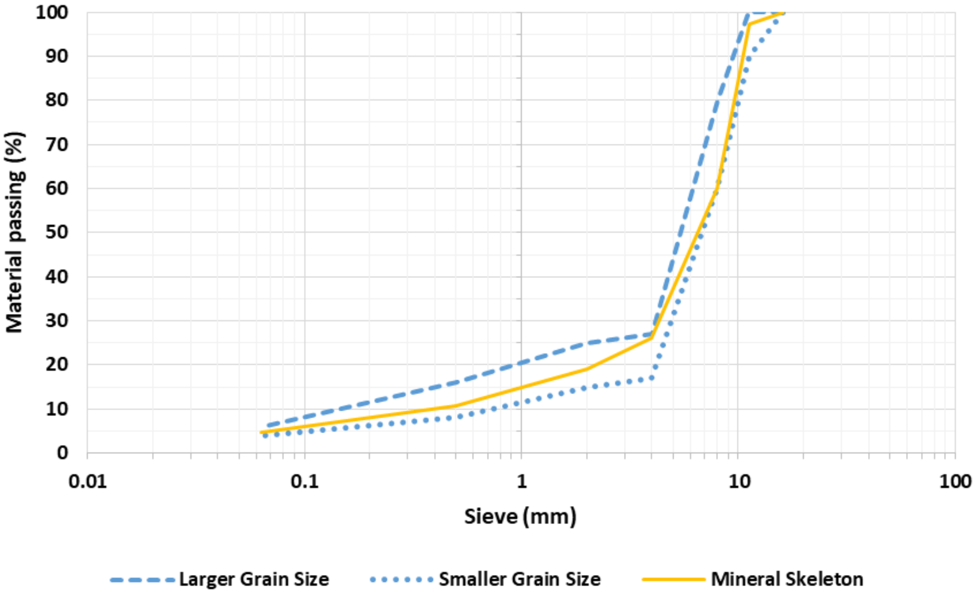

**Figure 4.3.1.** Mineral skeleton of the BBTM 11 mixture used in the study.

*4.3.3.2. Testing Plan.*

The testing plan followed in this study was divided into three main stages: (i) laboratory study (assessment of binders and design of the asphalt mixtures); (ii) analysis of mixture reproducibility in-plant; (iii) application of the mixture in a trail section.

The first stage, conducted in the laboratory, consisted of evaluating the characteristics of both types of binders as well as the properties of the designed mixtures. To assess the rheological behavior of the CRMB in comparison with the traditional PMB, complex modulus and phase angle were measured at different temperatures (10, 20, 30, 40, 45, 52, 58, 64, 70, and 80 °C, in order to perform a precise analysis of the rheological response of the two binders under severe thermal gradients) and a range of frequencies (from 0.1 Hz to 20 Hz), using a Dynamic Shear Rheometer (DSR) through a shear loading at a constant amplitude of 0.1% strain (using two specimens per binder). Similarly, this equipment was used to carry out the MSCRT (Multiple Stress Creep and Recovery Test) to evaluate the resistance of the binders to permanent deformations, along with their ability to recover the elastic strain under different levels of stress (0.1 and 3.2 kPa, applying loading cycles consisting of 1 second loads and a 9-second recovery phase) at various temperatures (45, 65, and 70 °C) and using two specimens per binder.

Regarding the design of the PMB-HMA and CRMB-HMA hot mixtures, the water sensitivity test [19], wheel tracking test [20], bulk density test [21], and air void content test [22] were conducted to determine optimal binder content. The water sensitivity test involves the manufacture of 6 test specimens with a diameter of 101.6 mm and a thickness of 60 mm, compacted with 50 blows on each side by a Marshall hammer. The specimens were subsequently divided into two sets of three specimens (a dry set and a wet set). The dry set was stored at room temperature in the laboratory (20 ± 5 °C), whereas a vacuum was applied to the wet set for 30 ± 5 min until a pressure of 6.7 ± 0.3 kPa was obtained. The specimens were then immersed in water at a temperature of 40 °C over a period of 72 hours. The next step was to perform an indirect traction resistance test on each of the cylinders (in both the dry set and the wet set). This was done at a temperature of 15 °C, and after a previous period of adjustment of 120 min to this temperature. The results of the experiment are expressed in terms of the retained strength of the test specimens after dividing the strengths of the wet specimens into the strengths of the dry specimens (ITSR, %).

The wheel tracking test involves the manufacture of two prismatic test specimens of 408 mm × 256 mm. Compaction was carried out by a roller compactor with a smooth steel roller to a thickness of 60 mm and a minimum density of 98% of the Marshall density. Two days after their compaction, both specimens were allowed to adjust to a temperature of 60 ± 1 °C, and then were tested at that temperature. The test itself involved the application of a load on the test specimen by means of the repeated passes of a loaded wheel. The load applied was 700 N and the number of passes was 10,000. The frequency of the device was 26.5 load cycles per minute. In each of the wheel passes, the resulting deformation on the test cylinder was measured. The objective of the test was to determine the wheel tracking slope (WTS, mm/103 load cycles) measured in the last 5000 load cycles.

Following this, and using the same design as that used for the CRMB-HMA, the workability of the CRMB-WMA at lower manufacturing temperatures (150 °C and 130 °C) was assessed in comparison with the conventional CRMB-HMA (which was manufactured at 175 °C). For this purpose, the density of the mixtures as a function of the compaction energy at different temperatures was analyzed (using a gyratory compactor), while evaluating the stiffness modulus at 20 °C [23] and los of particles at 25 °C [24] of the specimens obtained following the compaction process. Additionally, having selected the most appropriate manufacturing temperature of the CRMB-WMA, its properties and mechanical performance were compared with the conventional hot mixtures PMB-HMA and CRMB-HMA using the same tests described previously (water sensitivity, wheel-tracking, bulk density, and air void content).

Stiffness modulus was measured using the Indirect Tensile Stiffness Modulus Test (ITSM) as described in standard UNE-EN 12697-26 (Annex C). For the performance of the complete test, three test cylinders were manufactured for each of the mixtures studied. These specimens with a diameter of 101.6 mm and heights ranging from 35 mm to 75 mm were compacted with 50 blows on each side by a Marshall hammer. This test determined the stiffness modulus, based on a series of 15 load pulses with controlled strain and sinusoidal waveform of a three-second duration. The first ten pulses conditioned the equipment so that it could adjust to the size of the load and its duration. Values were obtained within the limits established by the standard (which establishes that the value of the test load factor should be between 0.5 and 0.7, the deformation value should neither be greater than 20 µm nor less than 3 µm, and the rise time should be 120–128 ms). The five subsequent pulses determined the stiffness modulus of the mix, which was the mean value of the five pulses. Once this value was calculated, the cylinder was turned to determine the modulus along the perpendicular diameter. This modulus should be 80–110% of the first value otherwise the test is not valid. The final value of the stiffness modulus of each specimen is the mean value of both diameters. The stiffness modulus of each mix is the mean value of the results obtained for the three test cylinders.

In the second study stage, following the design and evaluation of the mixtures at a laboratory level, a series of mixing processes were carried out in a real asphalt plant for each type of mixture (PMB-HMA, CRMB-HMA, and CRMB-WMA) to test their reproducibility. For this purpose, after their manufacture in-plant, the samples were taken to evaluate their mechanical response in the laboratory using the water sensitivity test [19] and wheel-tracking test [20]. Additionally, to assess their performance under severe climatic actions, the particle loss test [24] was also carried out under the following conditions: the response to water action was tested by comparing the results at 25 °C after conditioning in hot water at 60 °C for 24 hours in comparison with those obtained when tested in dry conditions at 25 °C; the effect of temperature was tested by conducting the test at 10, 25, and 60 °C; and the effect of aging was tested after conditioning at 165 °C for 12 hours. Furthermore, the bearing capacity of the mixtures manufactured in-plant was assessed through the stiffness test [23] at 5, 20, and 40 °C; cracking resistance was assessed at low temperatures using the TSRST (Thermal Stress Restrained Specimen Test, [25]) and fatigue cracking was evaluated using the UGR-FACT (University of Granada Fatigue Asphalt Concrete Test) at 10, 20, and 30 °C [26,27].

In the third phase of the study, the mixtures were used in the rehabilitation of a section of pavement on the A-92 highway (in the province of Granada, Spain). The location of the trial section was selected according to environmental and technical criteria. Regarding the first of these criteria, the section was placed in a mountain pass in a natural park where the use of CRMB-WMA (manufactured with recycled materials and at low temperatures) would help to reduce the negative impacts caused by road construction (in addition, the type of mixture used could reduce noise levels due to traffic rolling). Regarding the second criterion, the mixtures were evaluated under extreme conditions on account of the high volume of traffic (more than 18,000 vehicles per day, with a daily average of more than 3000 heavy vehicles) and extreme climate conditions (the section was placed at more than 1400 m above sea level, with the presence of snow during winter, and high temperaturas and many hours of solar radiation during summer) (Figure 4.3.2). In addition, this section was ideal for evaluating the real workability of the CRMB-WMA mixture since the transit time from plant to worksite was approximately 1 hour (Figure 4.3.3). The temperatures of the asphalt pavement operations were in a range between 12 and 28 °C.

**Figure 4.3.2.** View of the A-92 Highway, in winter (left) and summer (right) periods.

**Figure 4.3.3.** Distance from plant to the place of rehabilitation of the pavement (Source: Google Maps).

Finally, to complete the assessment of the performance of the CRMB-WMA in reference to the conventional high-performance mixtures (CRMB-HMA and PMB-HMA), a series of cores were obtained from the pavements to evaluate their bulk density [21] following compaction of the sections, whilst the stiffness test [23] and UGR-FACT (at 20 °C) were also carried out to evaluate their mechanical response.

### 4.3.4. Analysis of the Results.

#### *4.3.4.1. Laboratory Study.*

Figures 4.3.4 and 4.3.5 show the results obtained in the rheological study for the PMB and CRMB. In particular, Figure 4.3.4a shows the changes in the response of the binders through the Black diagrams (complex modulus and phase angle) depending on the test temperature and frequency, while Figure 4.3.4b displays the isochrones of the complex modulus and phase angle as a function of the temperatura at a constant frequency of 5 Hz. Figure 4.3.5 shows the results of the MSCRT through the elastic recovery and the permanent deformations with the Jnr parameter at 3.2 kPa.

Figure 4.3.4a shows the thermorheologically complex response (noted by the non-superposition of the curves at high temperatures) of the studied binders (due to the presence of the polymers). In these diagrams, higher phase angles and lower complex modulus are related to more viscous/flexible materials (or tested at higher temperatures), while lower phase angles and higher complex modulus are related to more elastic/rigid materials (or tested at lower temperatures). In this respect, both binders presented quite similar visco-elastic behavior. Nonetheless, it is seen that the CRMB led to a slightly more elastic performance, particularly at high temperatures where it presents a lower phase angle. This can also be observed in Figure 4.3.4b where both binders recorded similar isochrones, decreasing the complex modulus and increasing phase angle with an increase in the test temperature, but obtaining a slightly lower phase angle of CRMB at high temperatures in comparison with conventional PMB.

In Figure 4.3.5, it is seen that the CRMB (with a quantity of crumb rubber around 15% over the total weight of binder) offered higher elastic recovery and higher resistance to permanent deformations (around 40% lower Jnr values), regardless of the test temperature. These results are in consonance with those obtained on the frequency sweep tests. These results, therefore, indicate that the CRMB presented similar (or even superior) mechanical performance to conventional PMB, which makes it appropriate for its application in the manufacturing of the high-performance mixtures.

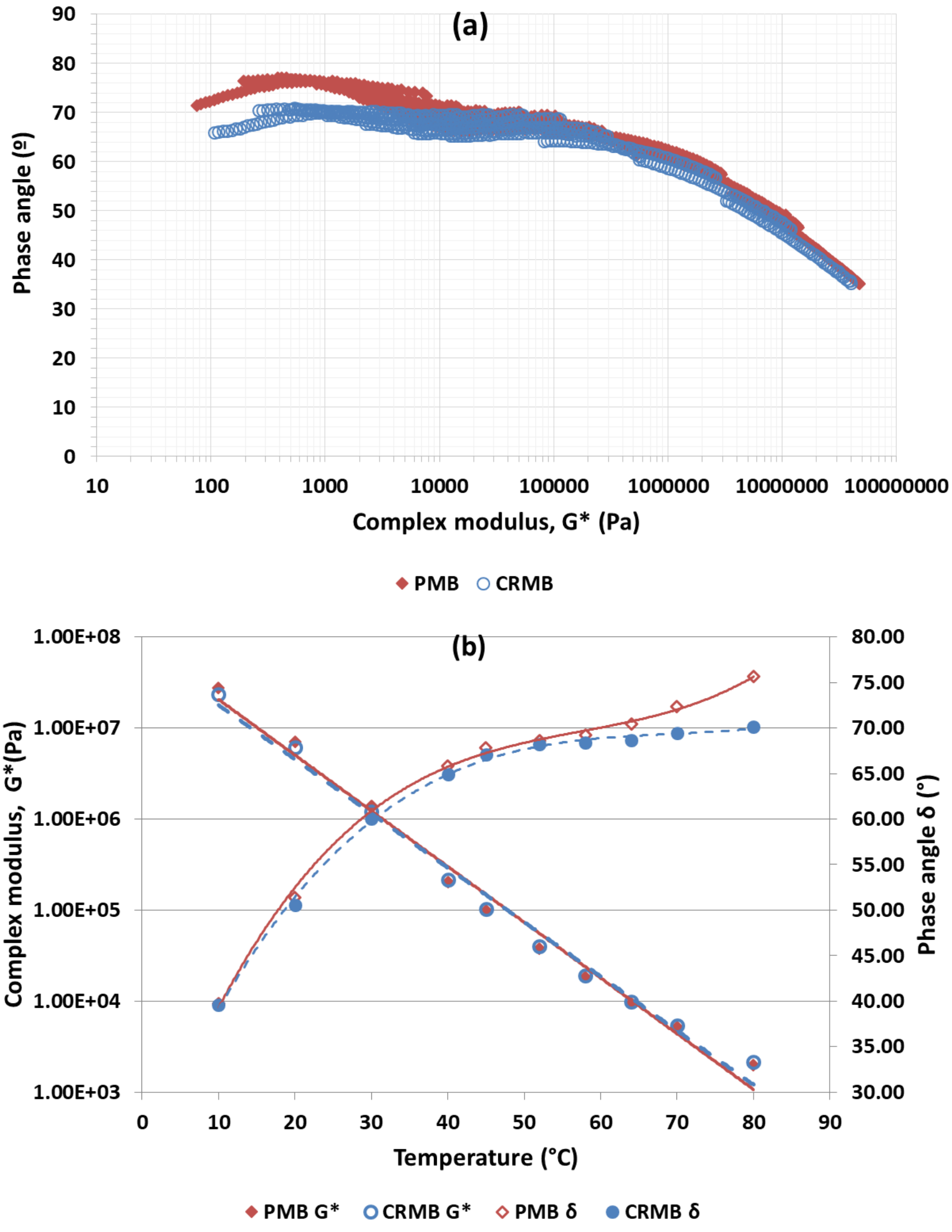

**Figure 4.3.4.** Results from the rheological study for the CRMB and PMB: (a) Black diagram; (b) Isochrones at 5Hz.

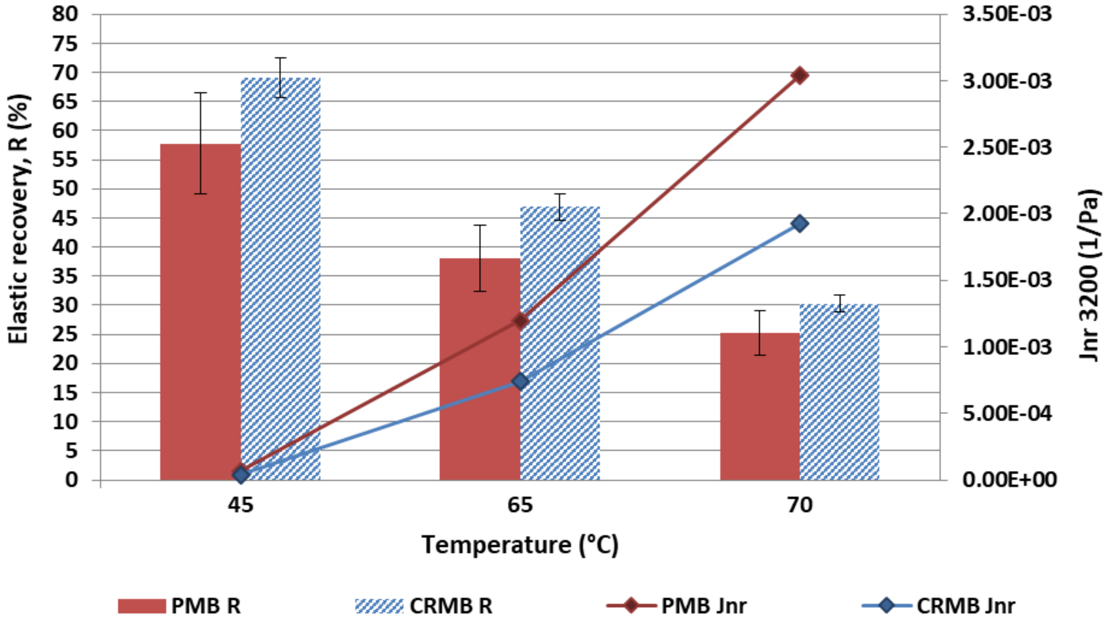

**Figure 4.3.5.** Results of the MSCRT at different temperatures.

Once the bitumens had been evaluated, the design of the bituminous mixtures was carried out. Table 4.3.3 lists the main properties obtained during the design tests carried out for the hot mixtures (PMB-HMA and CRMB-HMA) when selecting the optimal binder content (which was the same in both cases, i.e., 4.75% over the total weight of the mixture).

**Table 4.3.3.** Main characteristics of the mixtures designed in the laboratory.

| **Characteristics.** | **PMB-HMA** | **CRMB-HMA** | **CRMB-WMA** |
|---|---|---|---|
| Bulk density (Mg/m$^3$), EN 12697-6 | 2.146 | 2.134 | 2.137 |
| Air voids (%), EN 12697-8 | 16.5 | 18.0 | 17.9 |
| Indirect tensile strength at 15 °C (kPa), EN 12697-23 | 1287 | 1161 | 1182 |
| ITSR (%), EN 12697-12 | 91.9 | 90.7 | 94.0 |
| WTS at 60 °C (mm/10$^3$ ciclos), EN 12697-22 | 0.056 | 0.054 | 0.068 |

Based on the design of the CRMB-HMA, the design of the CRMB-WMA manufactured at a lower temperature was carried out (using the same binder content of 4.75% over the total weight of the mixture). Figure 4.3.6 presents the results obtained from studying the workability of the CRMB-WMA manufactured at 130 °C and 150 °C in reference to the conventional CRMB-HMA manufactured at 175 °C. The results confirmed that the decrease in manufacturing and compaction temperature (CRMB-WMA 150 and 130 °C) led to a significant reduction in density in comparison with the hot mixture used for reference. Nonetheless, the mixtures manufactured with the additive (CRMB-WMA) appeared to offer a lower reduction in density when using manufacturing temperatures of approximately 150 °C (with workability much more similar to that offered by the hot mixture). Similarly, Figure 4.3.7 shows that a decrease in manufacturing and compaction temperature led to a significant reduction in the mechanical performance of the mixtures (measured through stiffness modulus and particle loss). Nonetheless, it was again observed that using the additive allows for performance that is comparable to the conventional CRMB-HMA at 175 °C when the CRMB-WMA is manufactured at a temperature of around 150 °C. In particular, similar particle loss was observed despite recording lower stiffness (almost 45% less), which could be related to the lower oxidation of the binder during the manufacture of the CRMB-WMA.

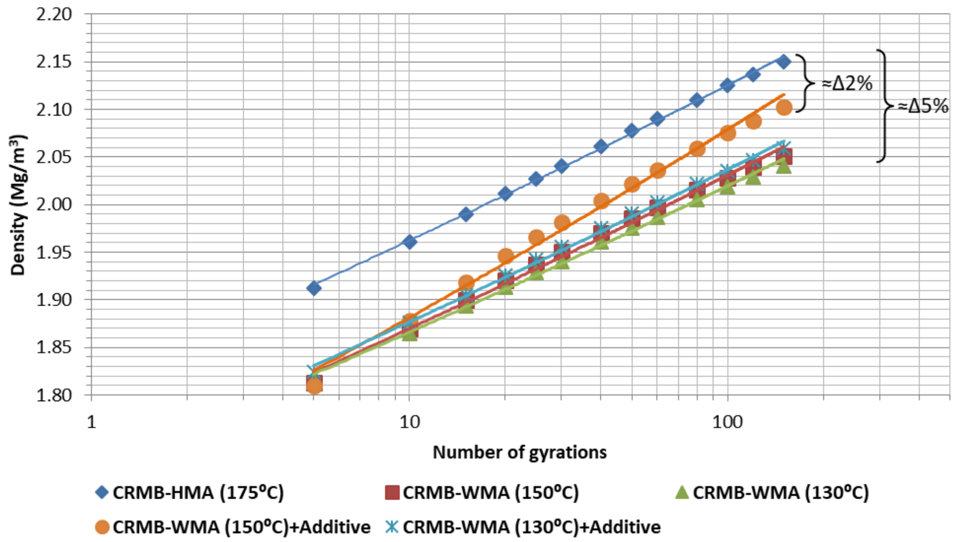

**Figure 4.3.6.** Curves of density versus energy of compaction at different temperaturas.

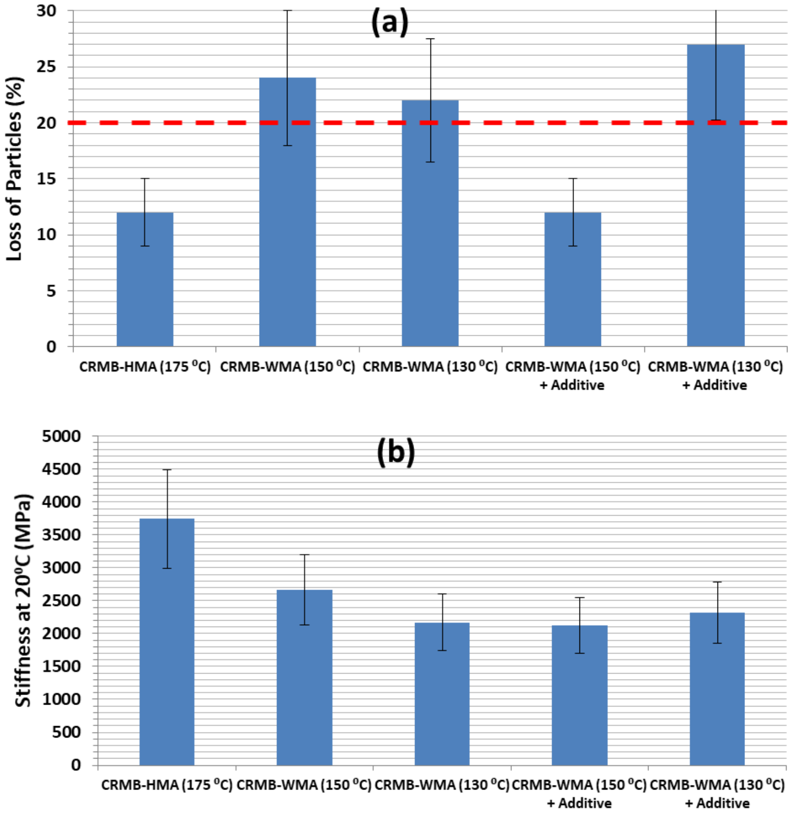

**Figure 4.3.7.** Results of the mechanical response of the CRMB mixtures: (a) particle loss; (b) stiffness at 20 °C.

Therefore, based on the previous results, it appears that the CRMB-WMA could be manufactured at temperatures of around 150 °C when using the chemical additive. In this respect, Table 4.3.3 demonstrates that the job mix formula of the CRMB-WMA manufactured at this temperature presented quite a similar density to the traditional high-performance mixtures as well as comparable tensile strength, susceptibility to water action (as measured by the ITSR-Indirect Tensile Strength Ratio), and resistance to permanent deformations (WTS parameter – Wheel Tracking Slope). This indicates that the CRMB-WMA manufactured at around 150 °C can be used in the construction or rehabilitation of road pavements.

### *4.3.4.2. Reproducibility of Mixtures in a Real Plant.*

After designing the mixtures in the laboratory, these were manufactured in-plant to analyze the reproducibility of the job mix formulas. In this case, and based on the results obtained in the previous stage, the manufacturing temperature used for the CRMB-WMA was set at 145 °C. Table 4.3.4 lists the data related to the consumption and production measured during the manufacture of the mixtures (CRMB-HMA and CRMB-WMA). Reducing the manufacturing temperature of the CRMB-WMA mixture led to an approximate 20–30% reduction in fuel consumption in-plant, which could partially compensate for the cost overrun associated with the use of the additive (the final extra cost estimated for the CRMB-WMA was lower than 0.6–0.7% in reference to the conventional HMA).

**Table 4.3.4.** Data from the production in-plant of the mixtures manufactured with the CRMB.

| Characteristics | CRMB-HMA | CRMB-WMA |
|---|---|---|
| Aggregates temperature (°C) | 172–178 | 146–148 |
| Flame of the drum dryer (%) | 72–81 | 37–59 |
| Fuel consumption (kg/tn) | 6.8–7.2 | 5.4–5.9 |

Table 4.3.5 shows the results of the water sensitivity and wheel tracking tests obtained for each type of material collected from the mixtures manufactured in the asphalt plant. It is proven that the reproducibility of the CRMB-WMA in-plant was adequate, again presenting comparable results to those measured for the conventional hot mixtures with both types of high-performance bitumens (PMB-HMA and CRMB-HMA), while obtaining similar results to those obtained in the laboratory study.

**Table 4.3.5.** Results of the water sensitivity tests and wheel-tracking tests for the mixtures manufactured in-plant.

| Characteristics | PMB-HMA | CRMB-HMA | CRMB-WMA |
|---|---|---|---|
| Indirect tensile strength at 15 °C (kPa), EN 12697-23 | 1111 | 1040 | 1108 |
| ITSR (%), EN 12697-12 | 90.5 | 90.9 | 90.1 |
| WTS at 60 °C (mm/$10^3$ ciclos), EN 12697-22 | 0.048 | 0.066 | 0.056 |

Figures 4.3.8 and 4.3.9 display the results obtained in the study of cohesion of the mixtures through the measures of particle loss under various climatic actions (water, temperature, and aging). The results show that lowering the test temperature led to a significant increase in particle loss due to the more brittle behavior of the bitumen, obtaining a ratio of increase of around 0.2%/℃ between 25–60 ℃, and 4.5%/℃ between 10–25 ℃. Nonetheless, a slight decrease in particle loss could be obtained when using the CRMB for both cases, the HMA and WMA present similar behavior despite the decrease in manufacturing temperature in the case of the WMA.

Similarly, Figure 4.3.8 indicates that the WMA mixture showed similar susceptibility to the increase in particle loss due to the action of water (around 5–7%, Figure 4.3.8a) or the effect of aging (between 1–9%, Figure 4.3.8b). Therefore, lowering the production temperature of the CRMB mixture allowed the material to show a similar mechanical performance to the traditional HMA (even under adverse climate actions) when using the chemical additive with a manufacturing temperature of approximately 145 ℃

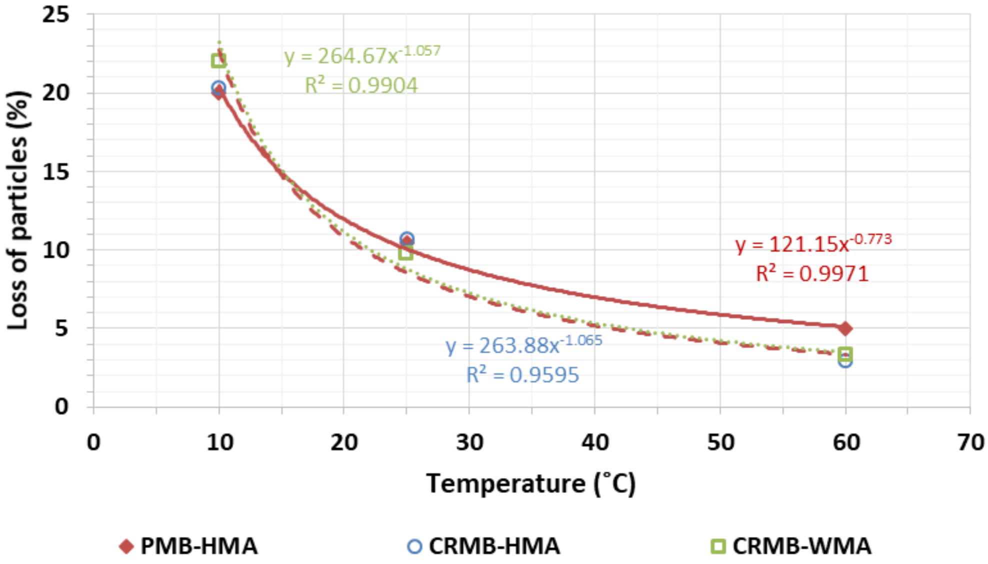

**Figure 4.3.8.** Results of particle loss at different temperaturas.

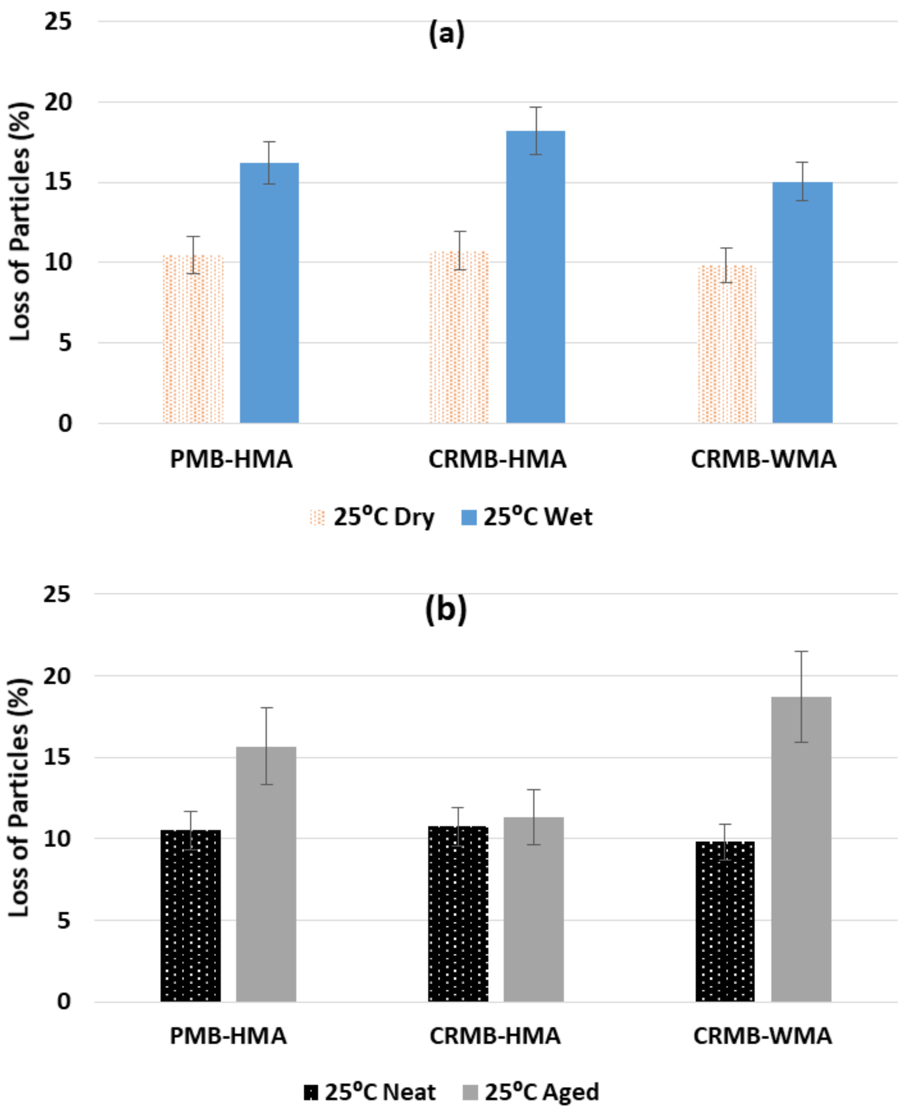

**Figure 4.3.9.** Particle loss for the mixtures following (a) water action and (b) aging simulation.

Figure 4.3.10 displays the results of the stiffness modulus of the various mixtures under different testing temperatures (5, 20, and 40 °C). Again it appears that the mechanical behavior of the CRMB-WMA was similar to that shown for the CRMB-HMA, and both present values close to those measured for the mixture produced with the traditional polymer-modified binder (PMB-HMA).

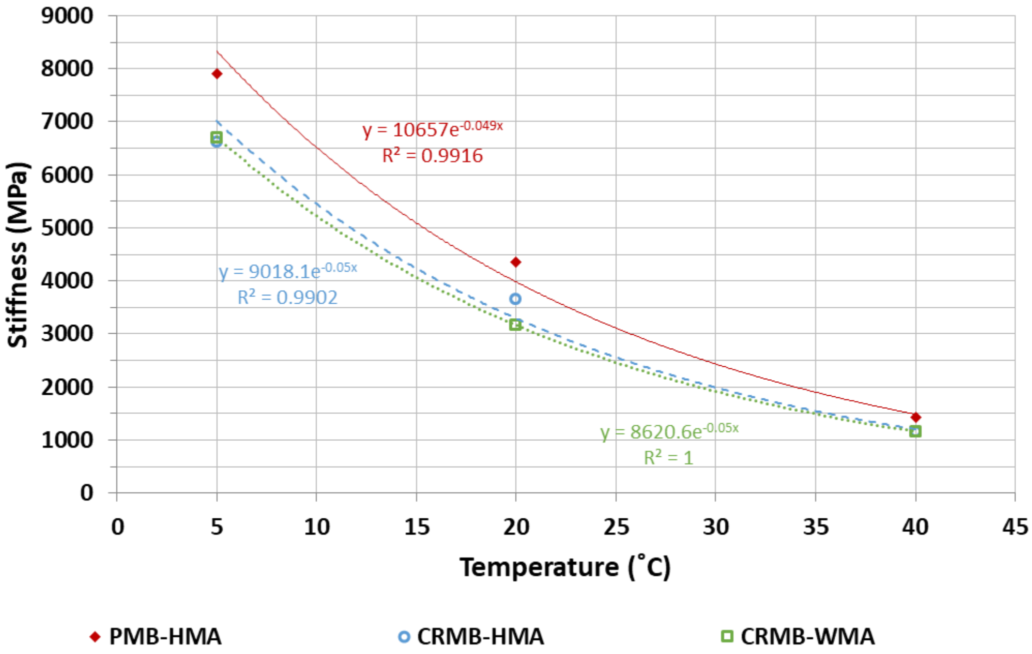

**Figure 4.3.10.** Stiffness modulus at different testing temperatures for the mixtures from the plant.

To analyze the resistance to cracking of the mixtures, Figure 4.3.11 displays the results of TSRST (which measures the development of the force acting on the specimen when decreasing the temperature up to material failure) while Figure 4.3.12 shows the results of UGR-FACT through the number of cycles to failure at different testing temperatures (Figure 4.3.12a) and the values of Mean Parameter Damage (Figure 4.3.12b) [28]. The results show that the three asphalt mixtures presented a comparable performance in terms of resistance to cracking. Nonetheless, it can be seen that, in general, the mixtures manufactured with CRMB showed slightly superior performance to that of the traditional PMB-HMA, regardless of the manufacturing temperature of the CRMB mixtures (showing higher resistance to cracking and lower temperature to failure; a slight increase in the number of cycles needed to produce fatigue cracking, and less damage in the specimen).

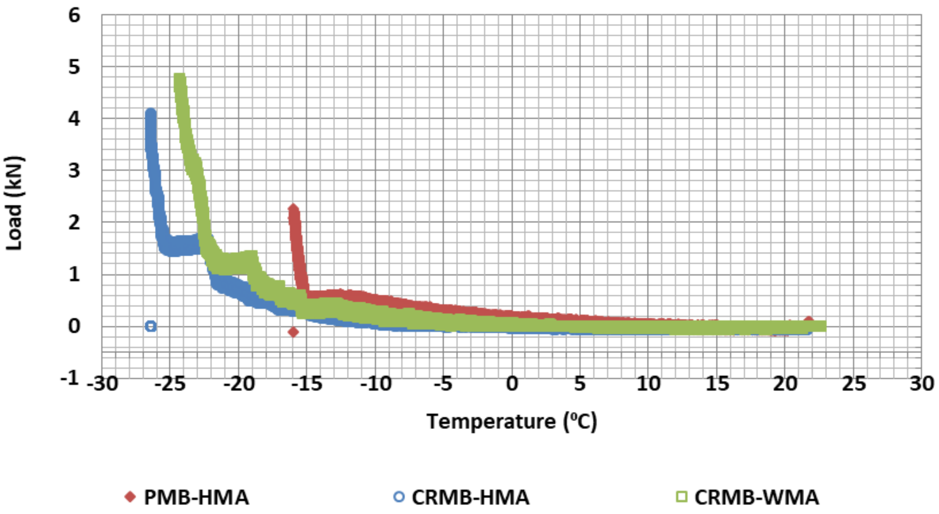

**Figure 4.3.11.** Results of TSRST for the different mixtures.

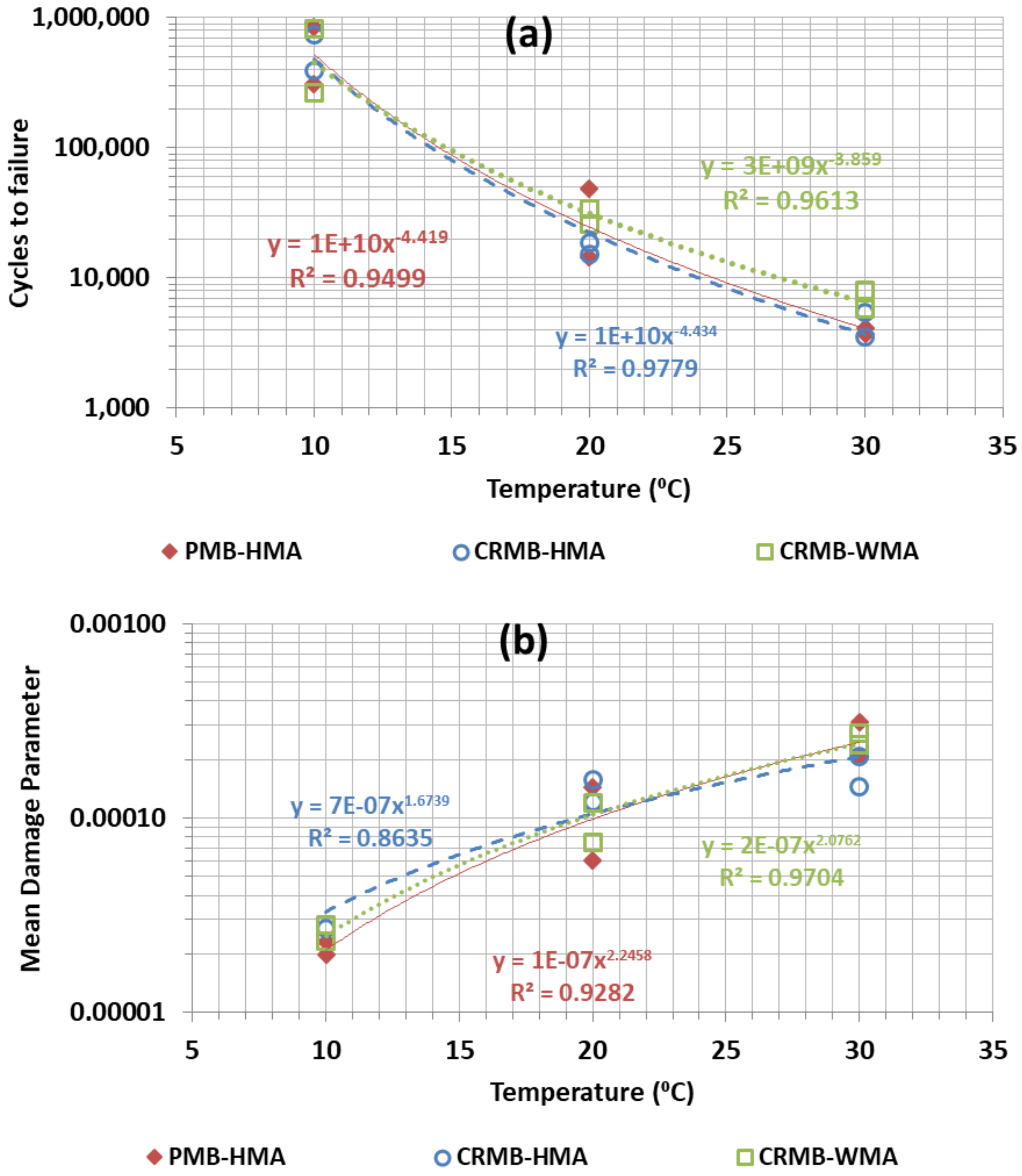

**Figure 4.3.12.** Results of UGR-FACT: (a) number of cycles to failure; (b) Mean Damage Parameter.

### *4.3.4.3. Trial Section.*

After demonstrating the adequate performance of the CRMB-WMA manufactured in the asphalt plant, the trial sections were constructed by using the equipment and machinery routinely employed with traditional mixtures. Figures 4.3.13–4.3.15 show that while few differences were observed in the visual aspect of the CRMB-WMA in reference to the CRMB-HMA or the PMB-HMA, there was a significant decrease in the temperature of the material following the spreading and compaction works (Figure 4.3.13 shows the aspect of the CRMB-WMA during spreading and after compaction).

**Figure 4.3.13.** Images from the spreading and compaction of the CRMB-WMA with a thickness of 3 cm.

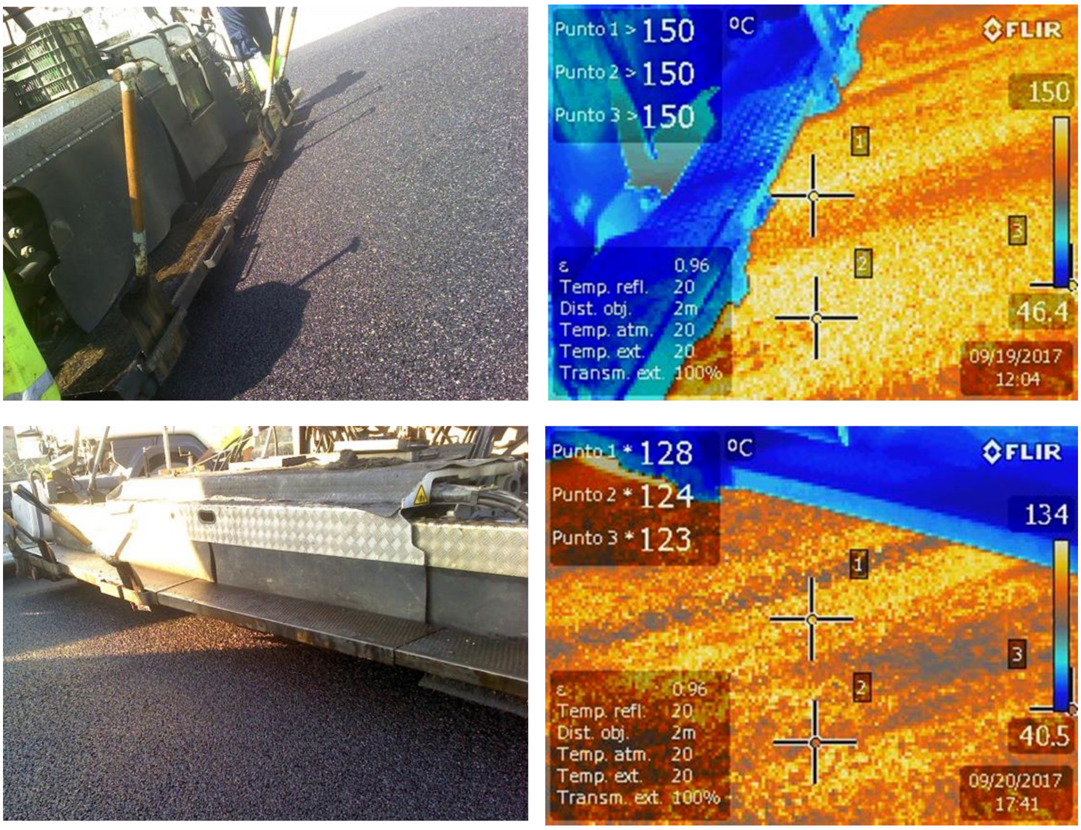

**Figure 4.3.14.** Comparison of the spreading temperature for the conventional CRMB-HMA (top) and the CRMB-WMA (bottom).

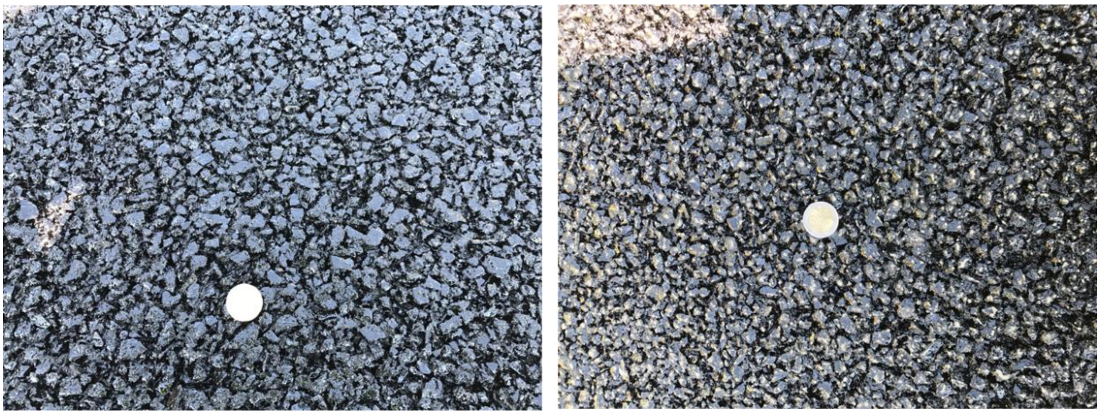

**Figure 4.3.15.** Visual appearance of the CRMB-HMA (left) and CRMB-WMA (right) after compaction.

For the cores collected from the trial sections, Figure 4.3.16 presents the density and stiffness data obtained at 20 °C for each core at the different kilometric points. As it can be observed, densities and stiffnesses obtained in the different sections offer a similar magnitude order and dispersion, which demonstrates that the mixtures studied have no differences in laying and compaction. It is clear that the density values for all the mixtures were even slightly higher than those measured in the laboratory (marked by the red line, which indicates adequate compaction of the materials), whilst the CRMB-WMA showed similar density and stiffness values to those of the reference mixtures, which confirms the satisfactory performance of this mixture despite the lower manufacturing temperature.

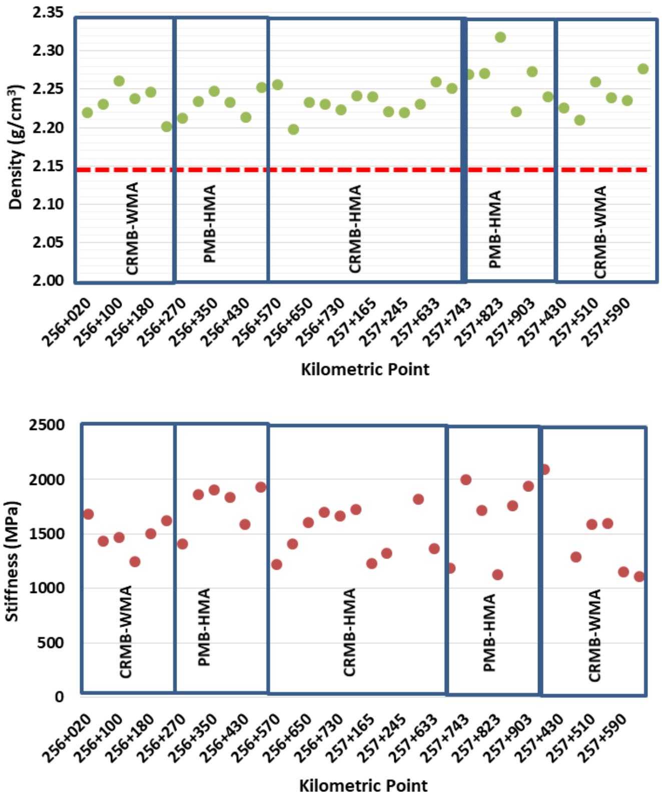

**Figure 4.3.16.** Results of density and stiffness (20 °C) for the cores obtained from different points of each trial section with the different mixtures analyzed.

Figure 4.3.17 displays the average results of the failure cycle and Mean Damage Parameter measured by the UGR-FACT at 20 °C for the various cores of each mixture. The graph shows that the fatigue life measured for the cores was slightly lower than that measured for the specimens manufactured in the laboratory, regardless of the type of mixture. Nonetheless, the results again show that all the mixtures presented comparable results, with the CRMB-WMA achieving an even longer fatigue life than the conventional HMA, thus providing evidence for the good response of this material in the long-term.

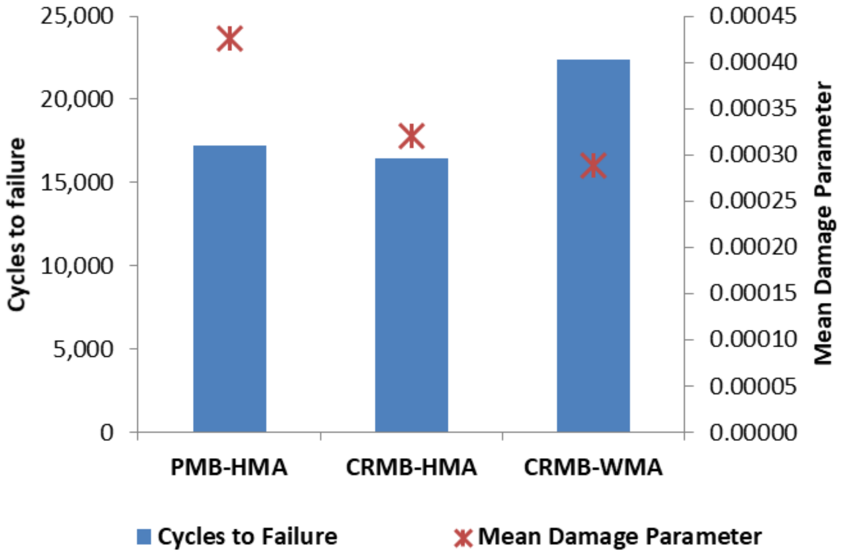

**Figure 4.3.17.** Results of UGR-FACT for the cores obtained from trial sections.

### 4.3.5. Conclusions.

This paper presents the results obtained in a research project focused on developing sustainable high-performance asphalt mixtures manufactured at low temperatures with crumb rubber-modified bitumen to be used in the construction/rehabilitation of road pavements subjected to high traffic volumes and severe climate conditions. On the basis of the results obtained, the following conclusions can be drawn:

1. The laboratory study of the crumb rubber-modified bitumen and the mixture manufactured with it at 30 °C lower than the hot conventional mixtures revealed a mechanical performance comparable to that recorded for traditional high-performance asphalt binders and hot mixtures in terms of elasticity, thermal susceptibility, workability, indirect tensile strength, water sensitivity, plastic deformations, and stiffness.

2. High-performance sustainable mixtures manufactured with crumb rubber-modified asphalt binders at 30 °C lower than the hot conventional mixtures can be produced in conventional asphalt plants and spread and compacted with conventional

equipment, achieving a material with a similar mechanical response to that of the reference hot mixtures (even higher in terms of resistance to fatigue and thermal cracking, particle loss, and permanent deformations) and a similar cost (the cost overrun associated with the use of additives can be partially compensated by the reduced energy consumption in-plant).

3. High-performance sustainable mixtures manufactured with crumb rubber-modified asphalt binders at 30 °C lower than the hot conventional mixtures can be transported long distances (one hour transport) without having workability or compaction problems.

4. Taken together, these findings suggest that sustainable high-performance mixtures presented in this paper could offer an interesting alternative to conventional hot mixtures for improving the durability of road pavements while reducing the environmental impacts associated with their construction/rehabilitation.

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## 4.4. Valoración económica de tecnologías sostenibles. Aplicaciones en conservación de la Red Autonómica de Carreteras de Andalucía.

### 4.4.1. Introducción.

Habiéndose probado que las mezclas asfálticas sostenibles son una alternativa a las mezclas calientes tradicionales como solución de conservación, queda por comprobar su viabilidad económica como solución para rehabilitación de firmes. Para ello, se hace un análisis de los costes adicionales asociados a la fabricación de este tipo de mezclas (aditivos y PNFVU), frente a los beneficios ligados a la producción, tanto por la disminución de consumo de combustibles fósiles al reducir su temperatura de fabricación, como por el decremento de los costes ambientales (menores emisiones, valorización de residuos, etc.).

### 4.4.2. Proyectos y obras de conservación.

La carretera A-4028 fue objeto de una rehabilitación mediante materiales asfálticos sostenibles. La mezcla utilizada fue una BBTM11B semicaliente (mediante la utilización de un aditivo) con betún modificado con PNFVU, es decir, la misma CRMB-WMA utilizada en el tramo de A-92 y descrita en el epígrafe 4.3.3.1. En la tabla 4.4.1 se recogen los principales datos de dicha obra.

**Tabla 4.4.1.** Características de la obra de la A-4028.

| OBRA | INVERSIÓN | FECHA DE EJECUCIÓN | CRMB-WMA EMPLEADAS |
|---|---|---|---|
| ACTUACIÓN DE SEGURIDAD VIAL EN EL TRAMO DE CONCENTRACIÓN DE ACCIDENTES EN LA A-4028, ENTRE LOS PP.KK. 0+000 Y 2+000 | 266.103,42 € | MAYO 2021 | 1.587 Tn |

### 4.4.3. Análisis de costes y beneficios.

Una vez producido el material asfáltico sostenible en una planta asfáltica real, se puede analizar la variación de costes respecto a la fabricación de mezclas tradicionales [70]. Así, para la mezcla CRMB-WMA, el resultado es el siguiente (Tabla 4.4.3):

**Tabla 4.4.2.** Variación de costes en mezclas asfálticas sostenibles respecto a las mezclas tradicionales.

| **ELEMENTO PRODUCTIVO** | **DIFERENCIA DE COSTE POR Tn DE CRMB-WMA** |
|---|---|
| ADITIVO | +1,20 €/Tn |
| PNFVU | +1,25 €/Tn |
| FUEL | -0,63 €/Tn |
| GASÓLEO | -0,12 €/Tn |
| **INCREMENTO DE COSTE DIRECTO** | **+1,70 €/Tn** |

El coste directo de la tonelada de CRMB-WMA para la obra de la A-4028 según su proyecto de construcción es de 43,70 €. Para mezclas convencionales habría que detraer 1,70 € según la Tabla 4.4.3, obteniendo un precio unitario de 42,00 €. Este escaso porcentaje de variación del 4,05% para esta mezcla sostenible queda compensado medioambientalmente con la valorización del polvo de caucho y la reducción de emisiones al bajar la temperatura de fabricación.

### 4.4.4. Conclusión.

Los materiales asfálticos sostenibles de altas prestaciones tienen aplicación directa en conservación de firmes de carreteras ya que, además de disponer de un alto rendimiento mecánico y funcional, su coste económico está perfectamente justificado.

# 5. CONCLUSIONES.

Atendiendo a los objetivos planteados en esta tesis para optimizar soluciones de conservación de firmes de carreteras, y según la investigación realizada cuya metodología y resultados más relevantes quedan recogidos en los artículos *Ageing of Crumb Rubber Modified Bituminous Binders under Real Service Conditions*, en la revista SUSTAINABILITY; *Analysis of the Real Performance of Crumb-Rubber-Modified Asphalt Mixtures*, en la revista MATERIALS; y *High-Performance Sustainable Asphalt Mixtures for High-Volume Traffic Roads in Severe Climates*, en la revista SUSTAINABILITY; se extraen las siguientes conclusiones:

1. Bajo condiciones climáticas y de tráfico severas, el betún modificado con PNFVU presenta características mecánicas y funcionales posteriores al envejecimiento semejantes a las que ofrece el tradicional betún modificado con polímero SBS, ofreciendo por tanto condiciones de servicio similares.

2. La densidad de las mezclas asfálticas en capa de rodadura estudiadas no se vio afectada por el tiempo en servicio, independientemente de que el ligante hubiera sido modificado con PNFVU o con el polímero SBS. Por contra, la rigidez sí se vio significativamente afectada debido a los efectos de los agentes ambientales, siendo el proceso de rigidización similar para las mezclas fabricadas tanto con el betún modificado con PNFVU como con el polímero SBS. En términos de resistencia a largo plazo, también ambas mezclas mantuvieron prestaciones similares en cuanto a fisuración por fatiga. En definitiva, bajo severas condiciones climáticas y de tráfico reales, las mezclas bituminosas fabricadas con betunes modificados con PNFVU presentan un envejecimiento y unas prestaciones mecánicas muy similares a las que ofrecen las mezclas bituminosas fabricadas con los tradicionales betunes modificados con polímero SBS.

3. El estudio de laboratorio de la mezcla fabricada a 30°C por debajo de las mezclas convencionales en caliente con betún modificado con PNFVU, reveló un comportamiento mecánico comparable al registrado para mezclas fabricadas en caliente con ligantes asfálticos modificados con el polímero SBS, en términos de elasticidad, susceptibilidad a la temperatura, trabajabilidad, resistencia a la tracción indirecta, sensibilidad al agua, deformaciones plásticas y rigidez. En cuanto a su ejecución a escala real, puede fabricarse en plantas de asfalto convencionales y extenderse y compactarse con equipos ordinarios, consiguiendo un material con una respuesta mecánica similar a la de las mezclas en caliente de referencia, que incluso es más alta en términos de resistencia a la fatiga y a la fisuración térmica, pérdida de partículas y deformaciones permanentes. Además, pueden transportarse largas distancias sin tener problemas de trabajabilidad o compactación.

4. El sobrecoste asociado al uso de aditivos para poder reducir la temperatura de fabricación, y a la introducción de PNFVU como modificador de los betunes, puede ser parcialmente compensado por la reducción del consumo de energía en planta.

Por tanto, las mezclas bituminosas fabricadas con betún modificado con PNFVU a 30°C por debajo de las mezclas convencionales en caliente, constituyen una alternativa óptima como solución para la conservación de firmes de carreteras ya que proporcionan características mecánicas y funcionales similares a las fabricadas con betún modificado con el polímero SBS, por lo que son de larga durabilidad. Pero además, tienen unas claras ventajas medioambientales ya que optimizan los recursos naturales según la economía circular: se valorizan residuos como el caucho, difícilmente degradable, y al fabricarse a menor temperatura, son más sostenibles medioambientalmente, reduciendo las emisiones de gases de efecto invernadero y el consumo de combustibles fósiles. Y todo ello con un coste económico similar al de las mezclas tradicionales.

# 6. FUTURAS LÍNEAS DE INVESTIGACIÓN.

Una vez alcanzados los objetivos de esta tesis doctoral, se identifican una serie de futuras líneas de investigación con la determinación de profundizar en la mejora de la conservación de firmes de carreteras:

En primer lugar, el comportamiento mecánico y funcional de los materiales asfálticos estudiados se ha analizado durante un período de 63 meses, que no alcanza el umbral de la vida útil establecido para este tipo de material, por lo que es de interés continuar con este estudio en el futuro. Se han extraído ya testigos a los 78 meses y debería proseguirse con campañas de extracción periódicas hasta alcanzar el agotamiento de la mezcla. Así, se podrían establecer los tiempos óptimos para renovación de las capas de firme sin esperar a su agotamiento final, hecho que implicaría el fresado previo con la consiguiente producción de un nuevo residuo y el correspondiente incremento en la inversión.

En segundo lugar, dado que la principal actividad en conservación de las administraciones titulares de carreteras consiste en la renovación de la capa de rodadura, y ésta en multitud de casos tiene que ser eliminada previamente debido a su agotamiento, debe plantearse la introducción de ese residuo de fresado en la futura capa de rodadura, estudiando la evolución de las propiedades mecánicas y funcionales de estas mezclas, y analizando una posible modificación de la normativa existente en la materia, que actualmente no admite esta posibilidad.

En tercer lugar, además del PNFVU, se pueden analizar otros polímeros (polietileno, polipropileno, etc.) como modificadores del betún, siendo residuos de otras producciones industriales que mejoren las propiedades mecánicas y funcionales de las mezclas bituminosas al igual que los estudiados en esta tesis.

Por último, se plantea la integración en las mezclas de sensores y/u otros dispositivos capaces de recibir/enviar información para ofrecer diferentes funciones que mejoren la seguridad vial, evaluando su estado de deterioro, midiendo velocidades, haciendo de estaciones de aforo y/o pesaje, etc.

# 7. REFERENCIAS BIBLIOGRÁFICAS.

En este epígrafe se relacionan las referencias de los apartados *1. Introducción*, *2. Metodología*, y *4.4. Valoración económica de tecnologías sostenibles. Aplicaciones en conservación de la Red Autonómica de Carreteras de Andalucía*. Las referencias utilizadas en cada uno de los tres artículos que conforman el compendio de publicaciones se adjuntan al final de cada uno de ellos.

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