

## Article

# Ageing of Crumb Rubber Modified Bituminous Binders under Real Service Conditions

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**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.

**Keywords:** asphalt; crumb rubber; rheology; field performance



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## 1. 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 valorisation 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.

## 2. Methodology

### 2.1. Materials

This paper focuses on the study of 4 sections (Figure 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 gap-graded 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 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 ( $15 \pm 0.5\%$ ) in order to prevent these variables from affecting the study conducted. The service conditions of the highway sections studied are summarised in Table 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 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)             | 8000                                                                                                                                                                                                               | 18,000                                                                                                                                                                                                                     | 11,000                                                                                                                                                                                                                |
| Percentage of heavy traffic (of the total number of vehicles) | 8                                                                                                                                                                                                                  | 17                                                                                                                                                                                                                         | 7                                                                                                                                                                                                                     |
| Climate conditions                                            | ~750 m above sea level; rarely frost/snow on the road surface during autumn/winter; maximum average temperatures in summer $\sim 36^\circ\text{C}$ ; minimum average temperatures in winter $\sim 4^\circ\text{C}$ | ~1400 m above sea level; very frequent frost/snow on the road surface during autumn/winter; maximum average temperatures in summer $\sim 30^\circ\text{C}$ ; minimum average temperatures in winter $\sim 1^\circ\text{C}$ | ~1100 m above sea level; frequent frost/snow on the road surface during autumn/winter; maximum average temperatures in summer $\sim 33^\circ\text{C}$ ; minimum average temperatures in winter $\sim 4^\circ\text{C}$ |

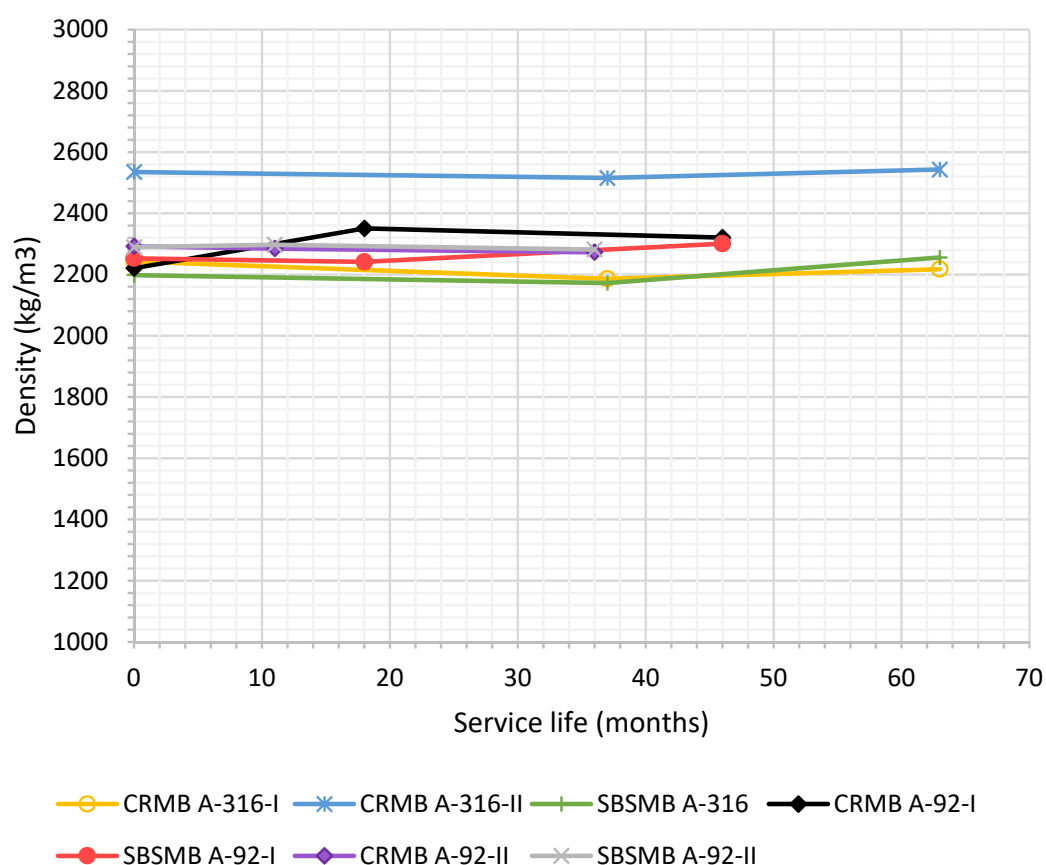
## 2.2. Testing Plan

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 under study (CRMB, CRMB (CB) and SBSMB) were analysed prior to and subsequent to mixture manufacture. The latter analysis took place at different times (Table 2) depending on the core extraction campaign. Figure 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 remain 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 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 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 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 then 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 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 s of duration were applied to the binder specimens with a rest period of 9 s 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 ( $J_{nr}$ ) parameters. The

parameter  $R$  can identify and quantify how the polymer is working in the binder, while  $J_{nr}$  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 ( $\Delta\epsilon_{nr}$ , in %/cycle, Equation (1)) and average recovered strain ( $RS_{15-30}$ , in %/cycle), which was the average absolute recovered strain from each cycle measured from the 15th cycle to the 30th cycle.

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

where  $\epsilon_{nr30}$  is the cumulative non-recoverable deformation after 30 load cycles and  $\epsilon_{nr15}$  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  $\Delta\epsilon_{nr}$  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.

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

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

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.

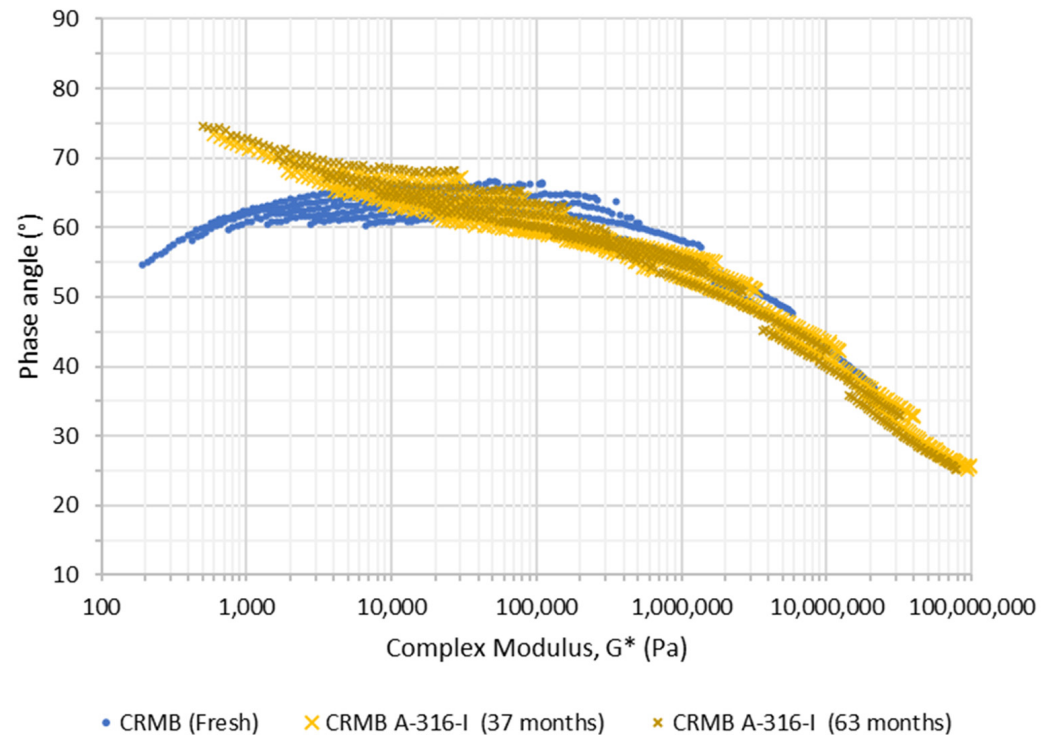
$$L - Index = \frac{F}{\tan RC} = \frac{\Delta\epsilon_{nr} \sqrt{\Delta\epsilon_{nr}^2 + RS_{15-30}^2}}{RS_{15-30}} \quad (4)$$

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  $F$  ( $F_{45-70}$ , obtained from the norm of the vector formed by the  $\Delta\epsilon_{nr}$  and  $RS_{15-30}$  values at 45 and 70 °C) and the loss of  $RC$  ( $RC_{45-70}$ ) can be utilised to determine the temperature susceptibility of the binder evaluated (Figure 3). Based on these considerations, the T-Index (Equation (5)) can be obtained to determine the resistance of asphalt binders to temperature variations.

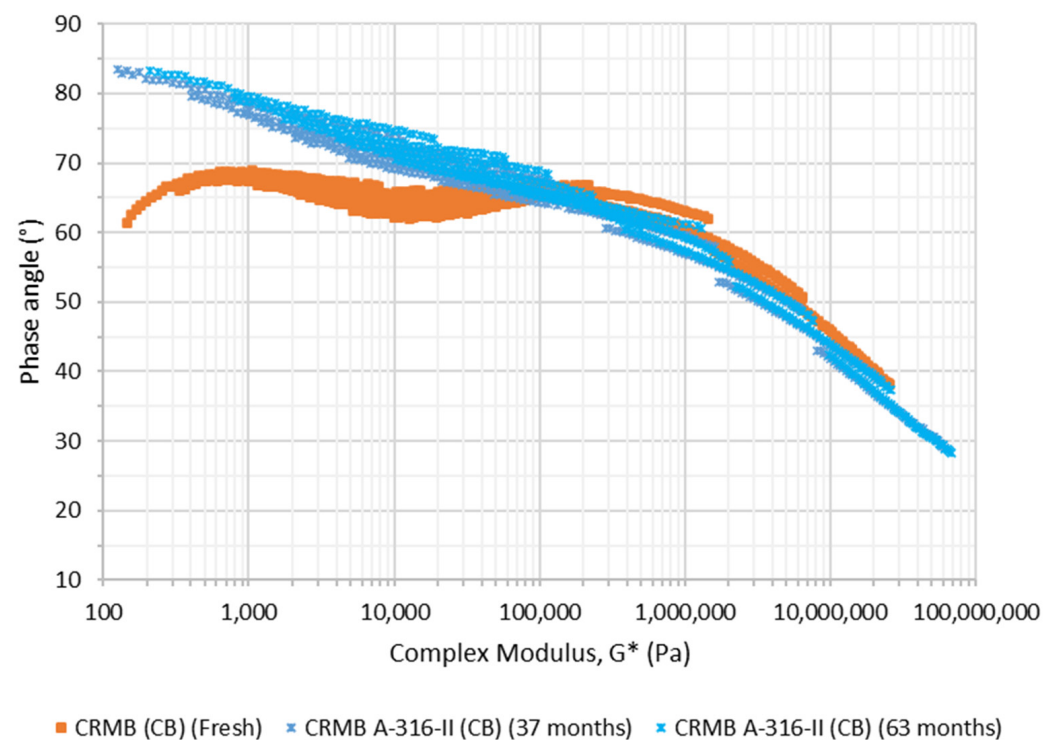
$$T - Index = F_{45-70} \frac{RC_{45} - RC_{70}}{RC_{45}} \quad (5)$$



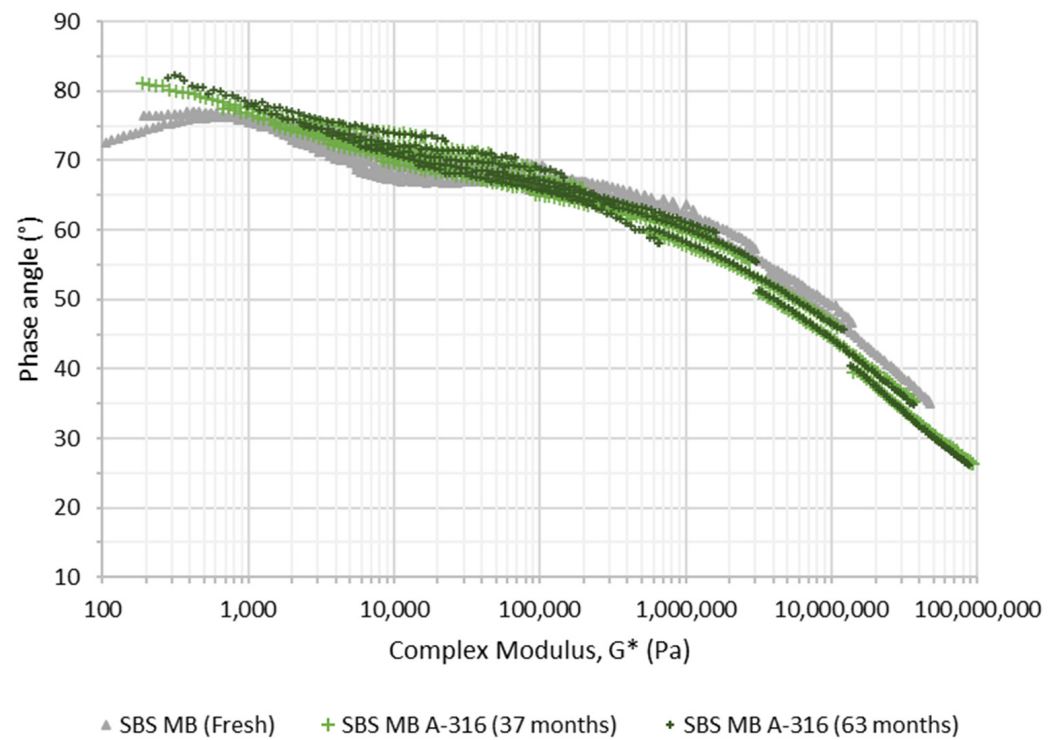
more brittle (similar to the CRMB) at higher temperatures, which inferred that it was able to maintain the same phase angles as the fresh SBSMB: this was also in contrast with the observations made at the laboratory, where the values of the phase angle in aged binders were reduced regardless of the temperature [27,28].



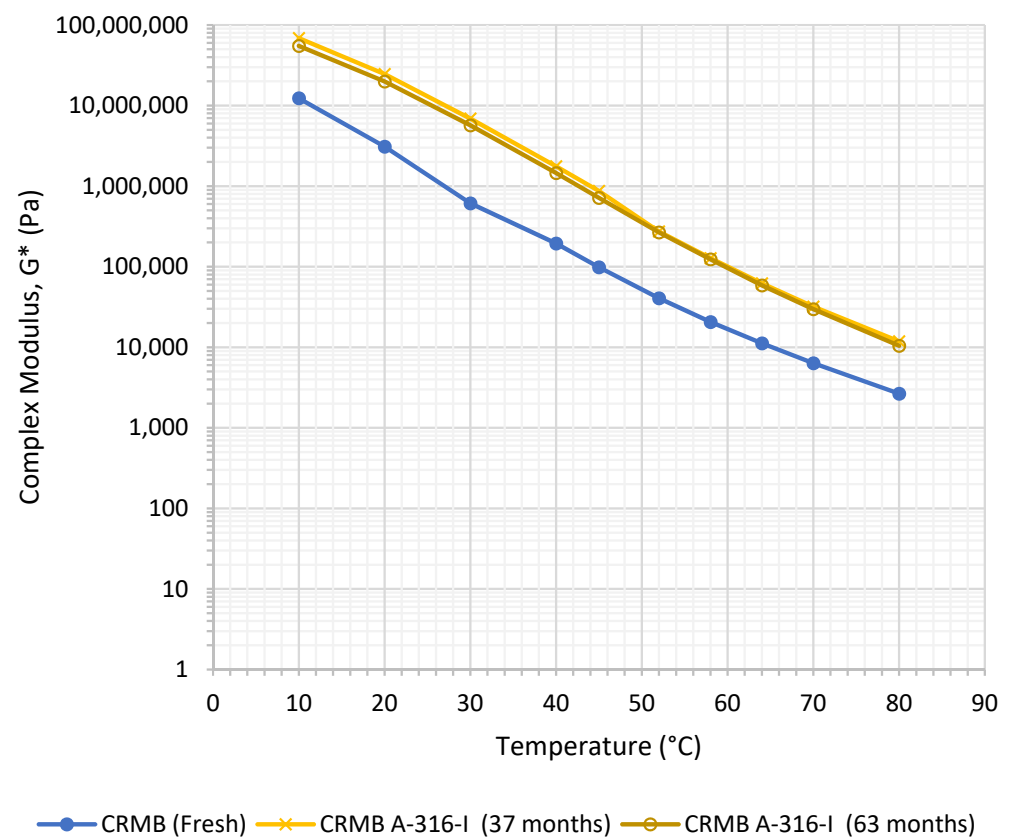
**Figure 4.** Black diagrams of the CRMB used in the A-316-I at different service-life periods.



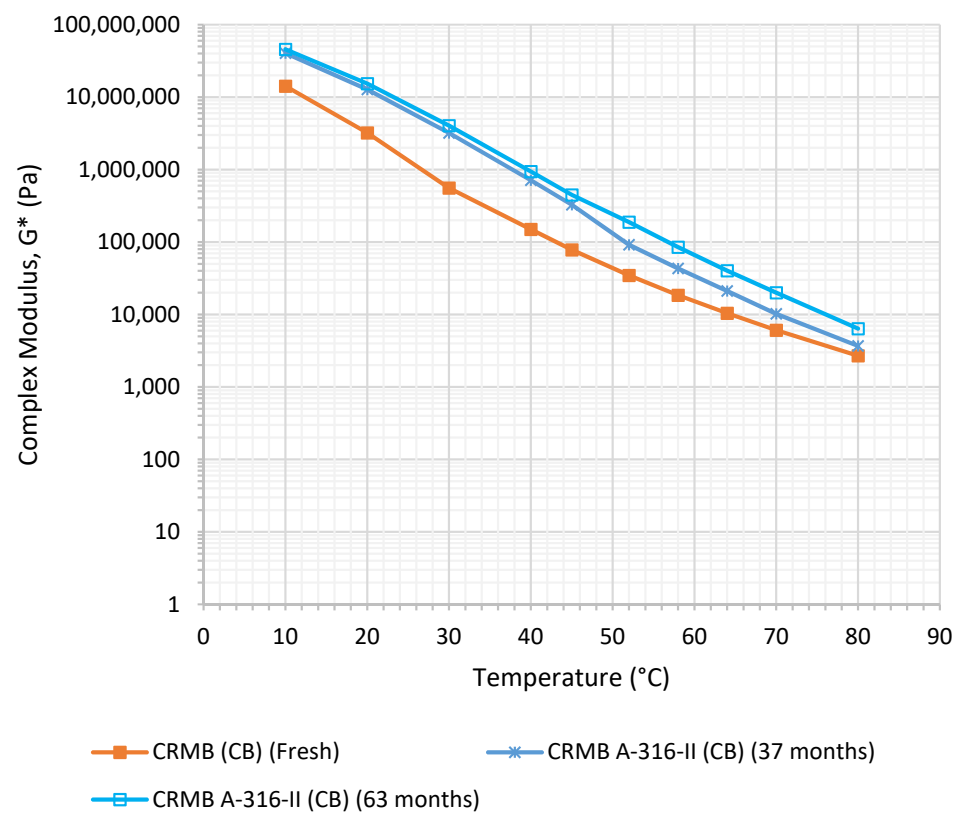
**Figure 5.** Black diagrams of the CRMB (CB) used in the A-316-II at different service-life periods.



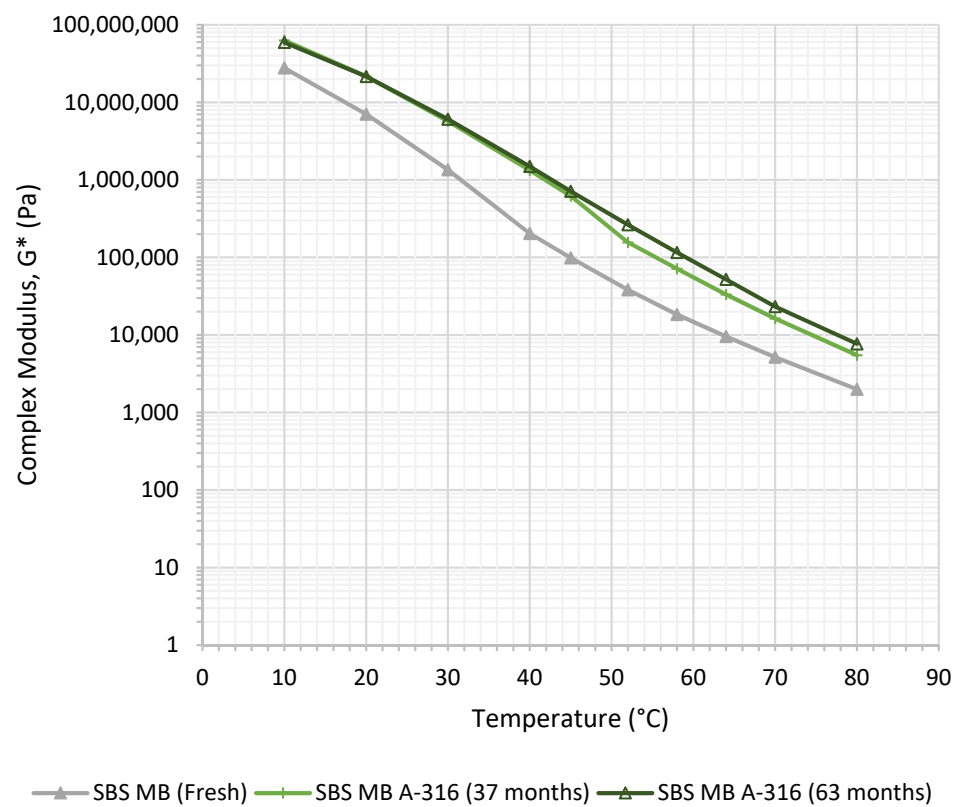
**Figure 6.** Black diagrams of the SBSMB used in the A-316 at different service-life periods.



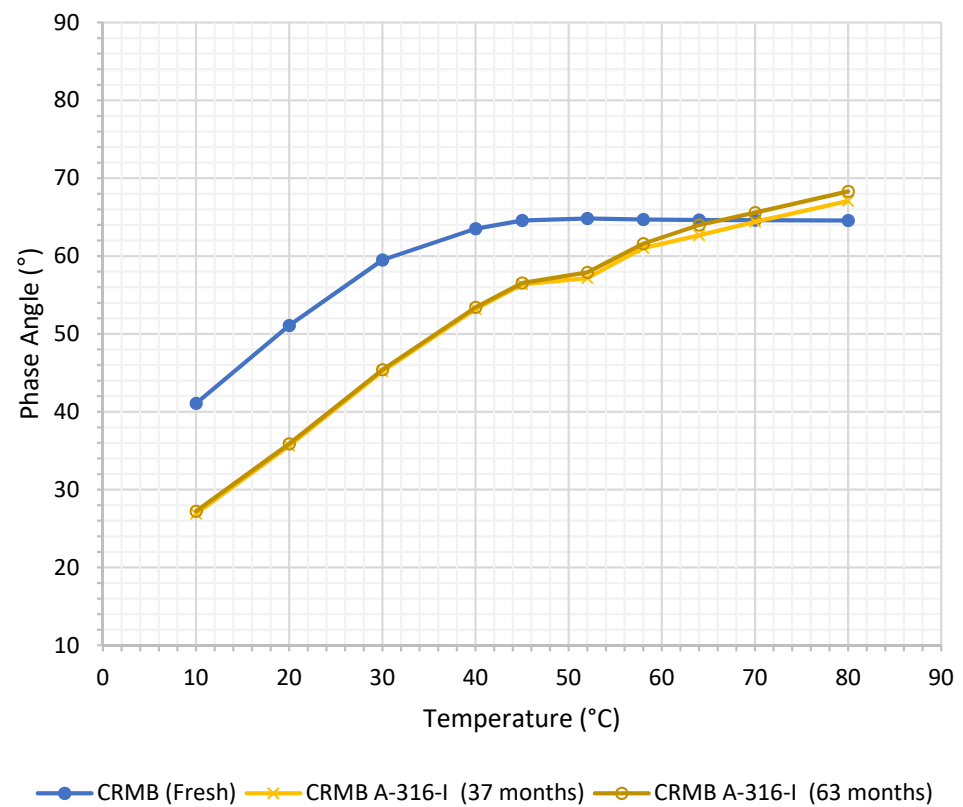
**Figure 7.** Isochrone curves at 5 Hz of the complex modulus of the CRMB used in the A-316-I at different service-life periods.



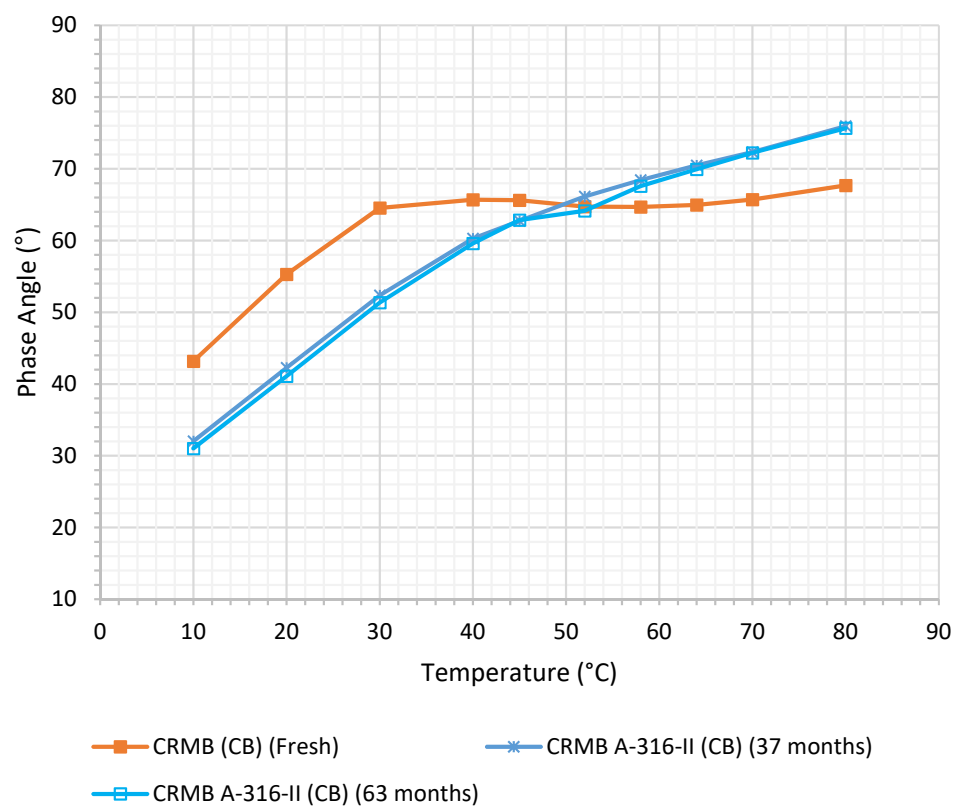
**Figure 8.** Isochrone curves at 5 Hz of the complex modulus of the CRMB (CB) used in the A-316-II at different service-life periods.



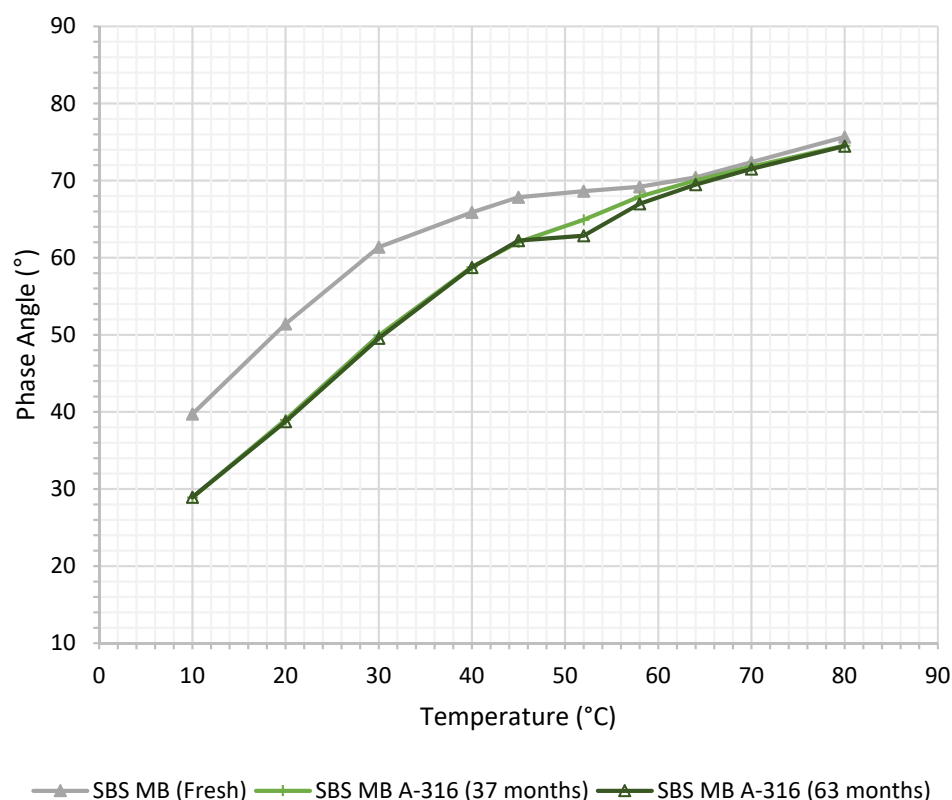
**Figure 9.** Isochrone curves at 5 Hz of the complex modulus of the SBSMB used in the A-316 at different service-life periods.



**Figure 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 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 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 13–16). Both types of modified bitumen (CR and SBS) experienced an increment in their complex modulus regardless of the test temperature (Figures 17–19). 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 20–24).

The MSCR test findings (Figures 25–31) corroborated that the stiffening process suffered by the binders during their service life reduced their susceptibility to plastic deformations (lower values of  $J_{nr}$ ), 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.

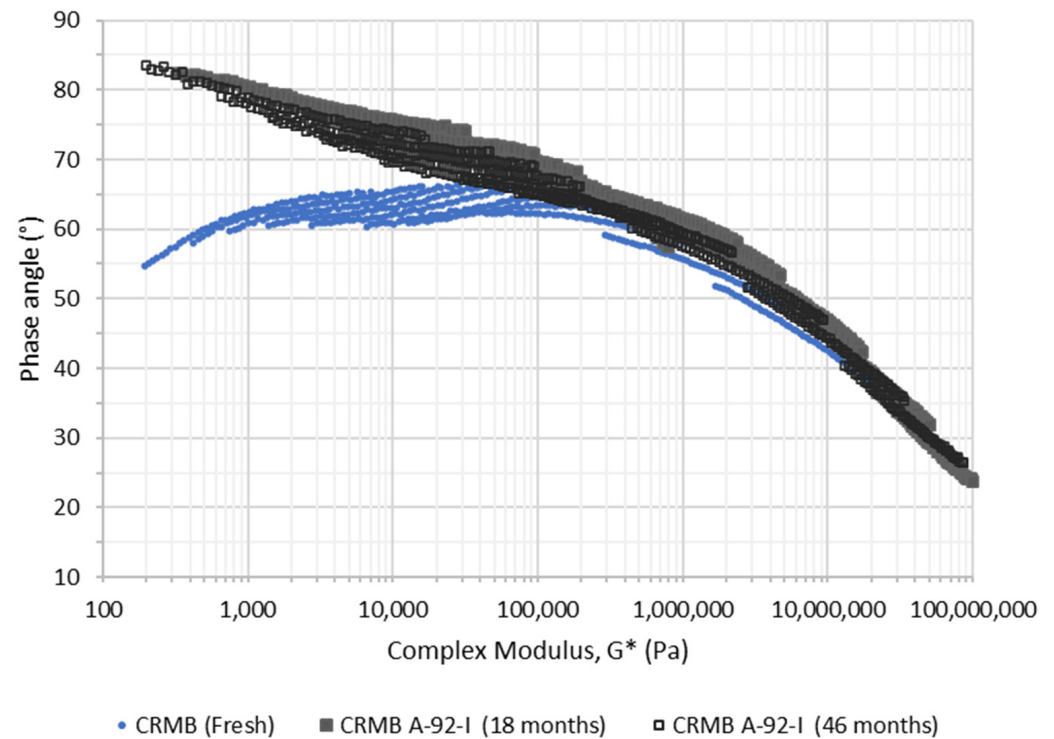


Figure 13. Black diagrams of the CRMB used in the A-92-I at different service-life periods.

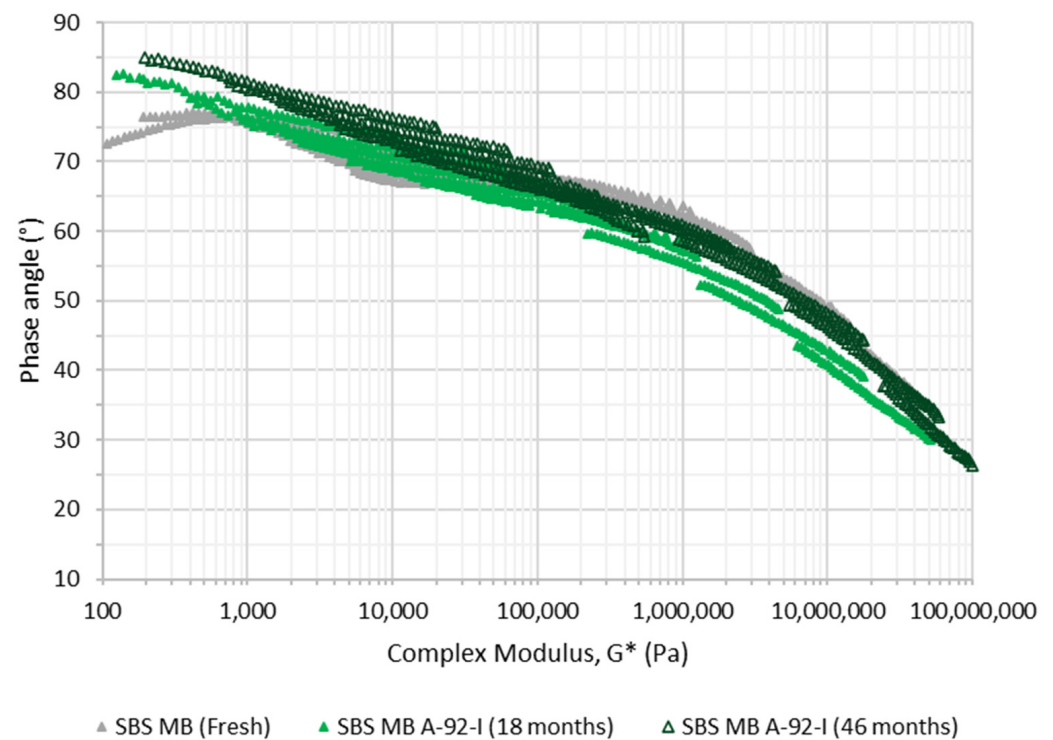


Figure 14. Black diagrams of the SBSMB used in the A-92-I at different service-life periods.

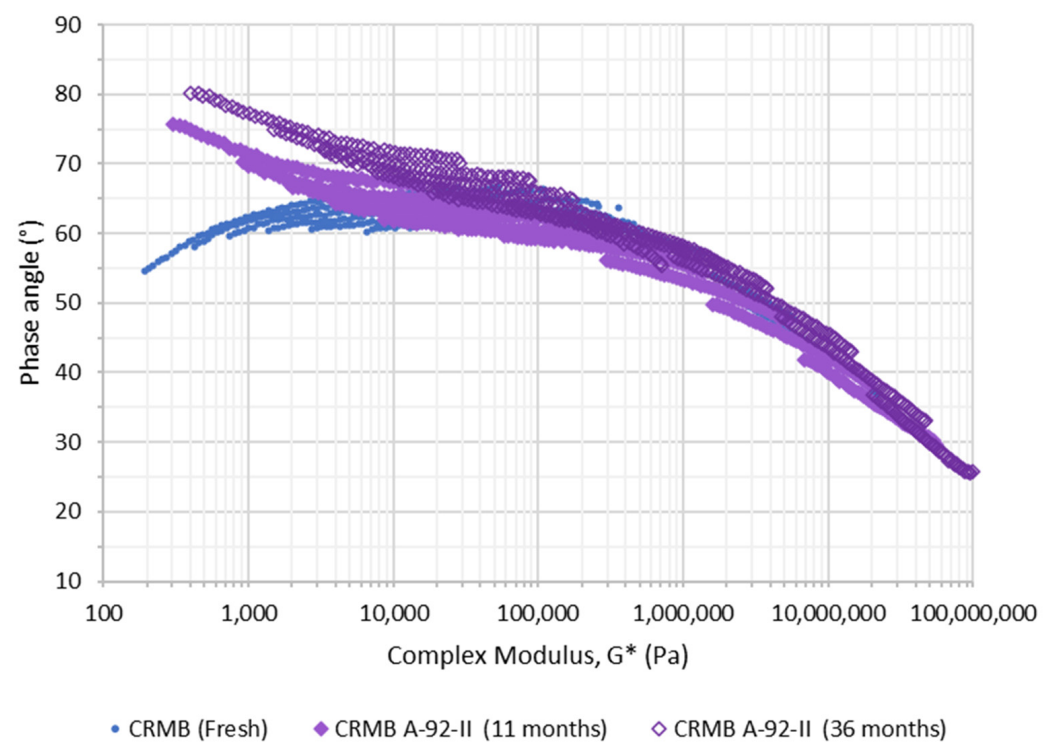


Figure 15. Black diagrams of the CRMB used in the A-92-II at different service-life periods.

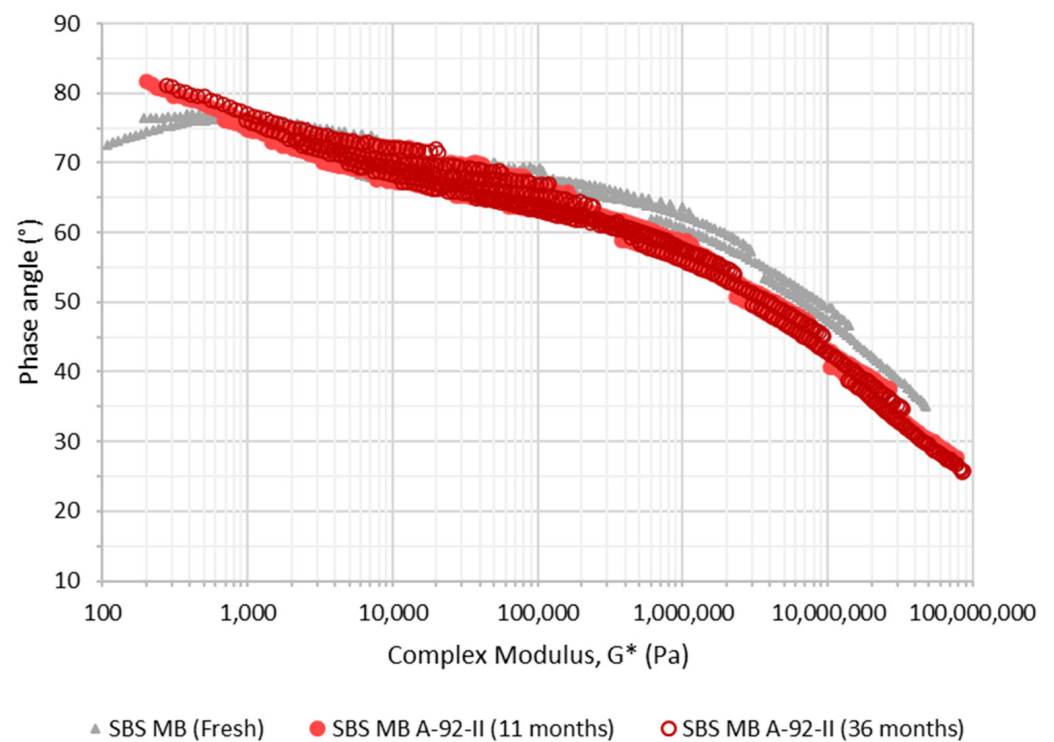
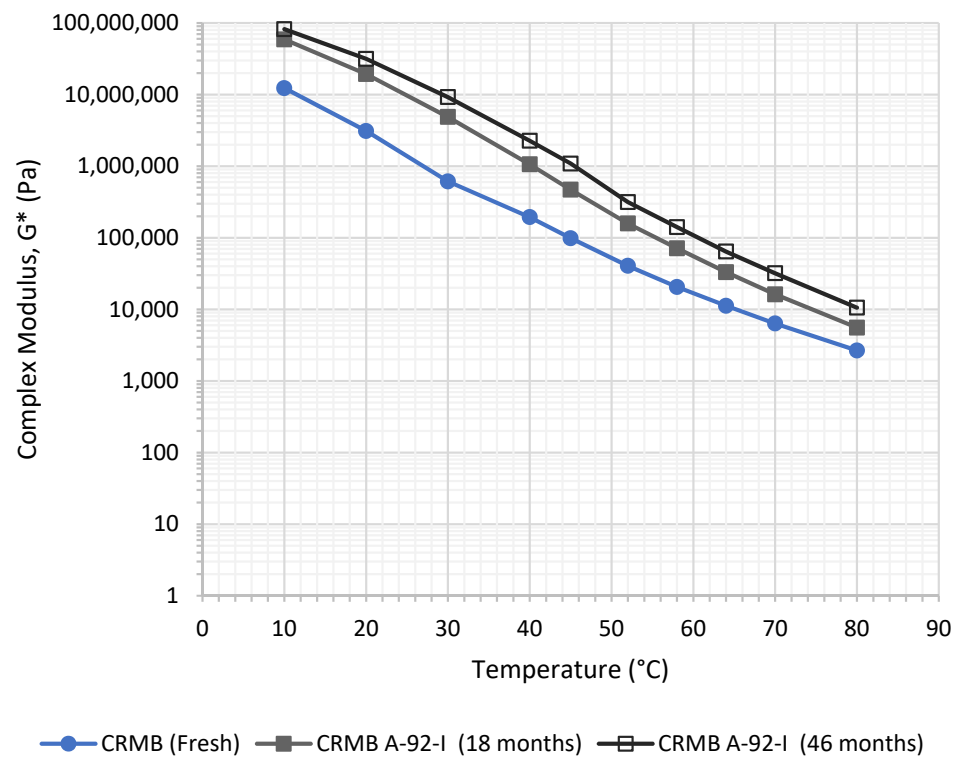
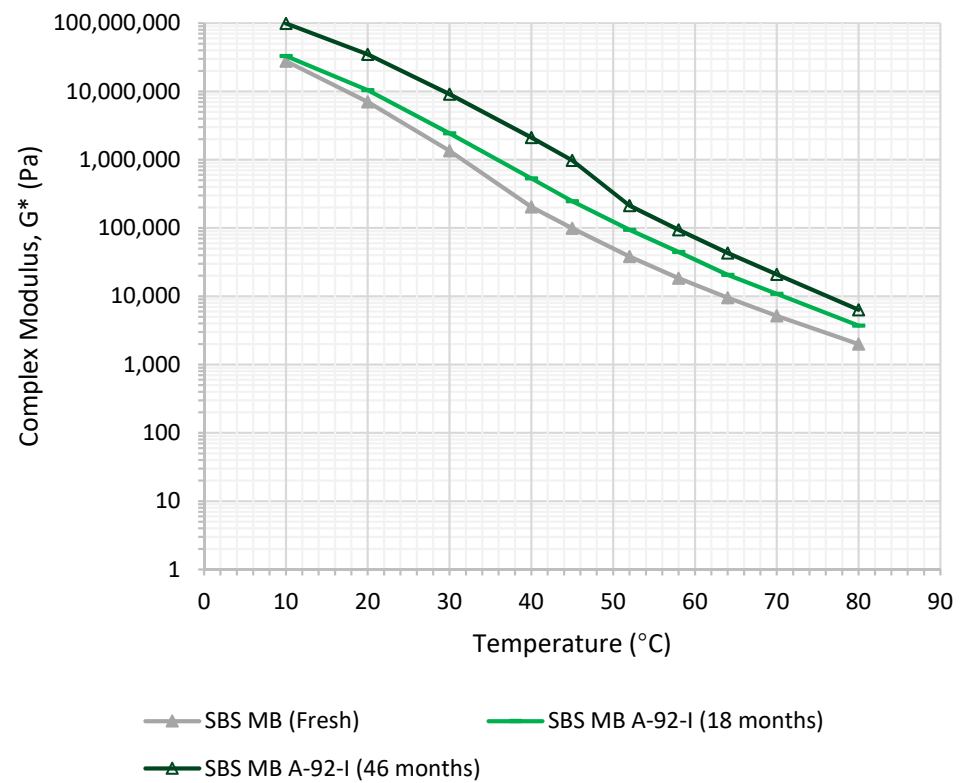


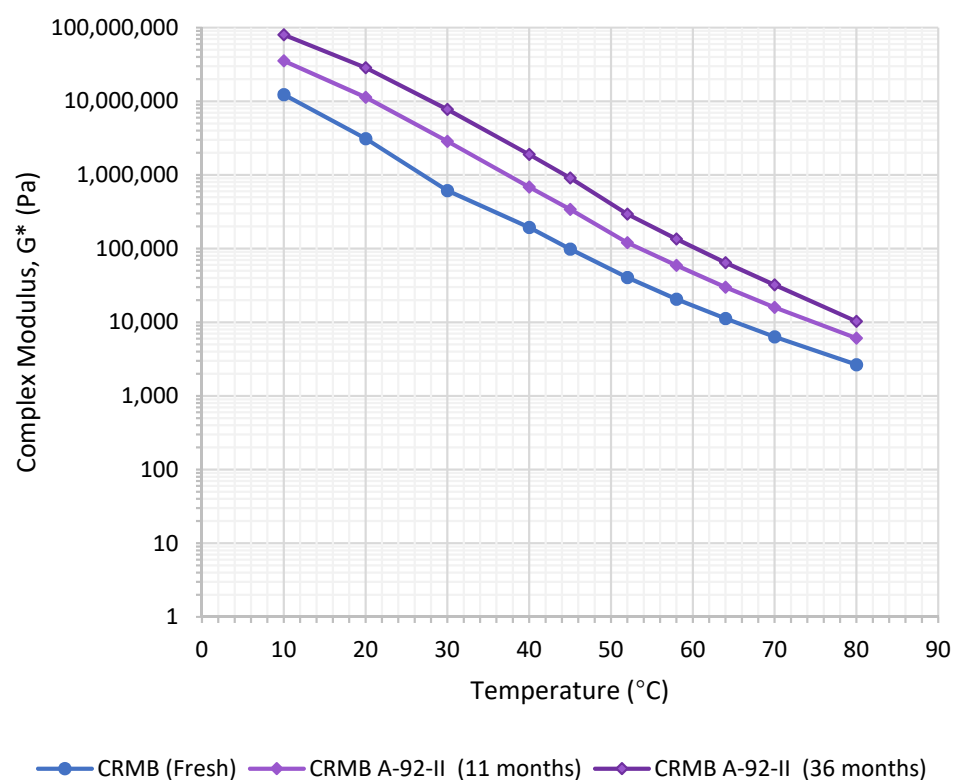
Figure 16. Black diagrams of the SBSMB used in the A-92-II at different service-life periods.



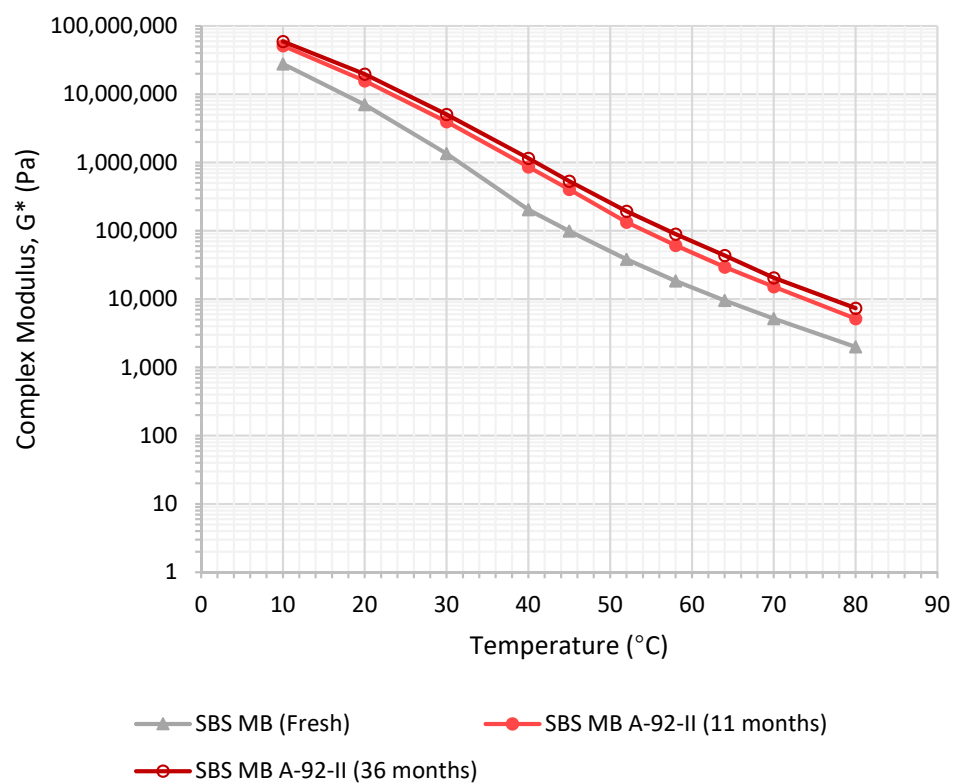
**Figure 17.** Isochrone curves at 5 Hz of the complex modulus of the CRMB used in the A-92-I at different service-life periods.



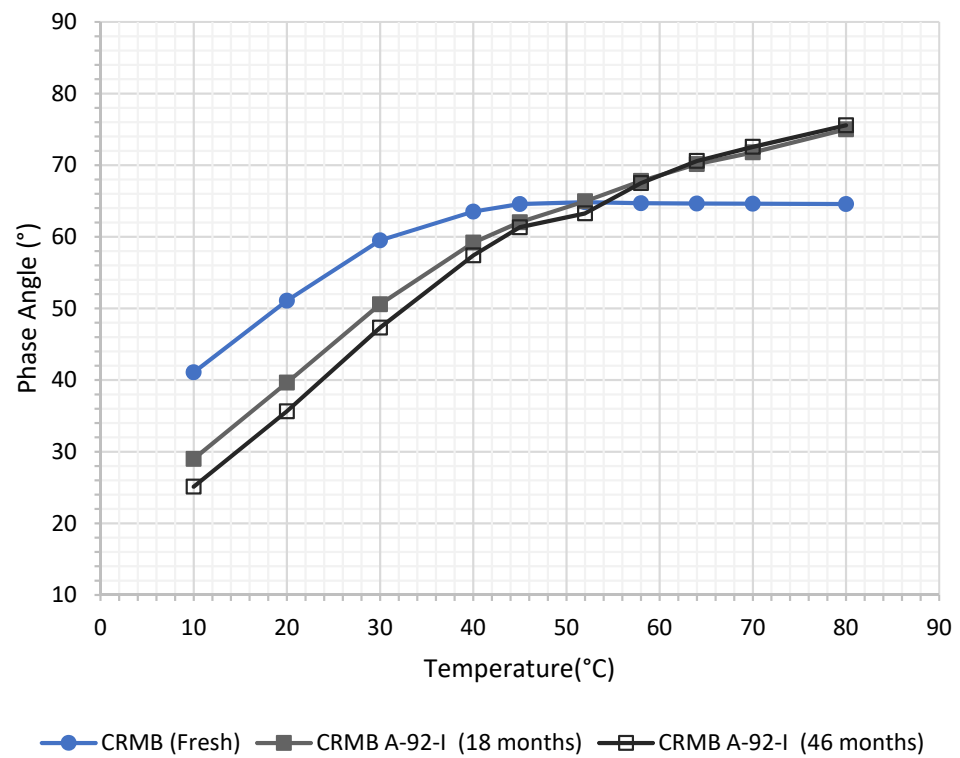
**Figure 18.** Isochrone curves at 5 Hz of the complex modulus of the SBSMB used in the A-92-I at different service-life periods.



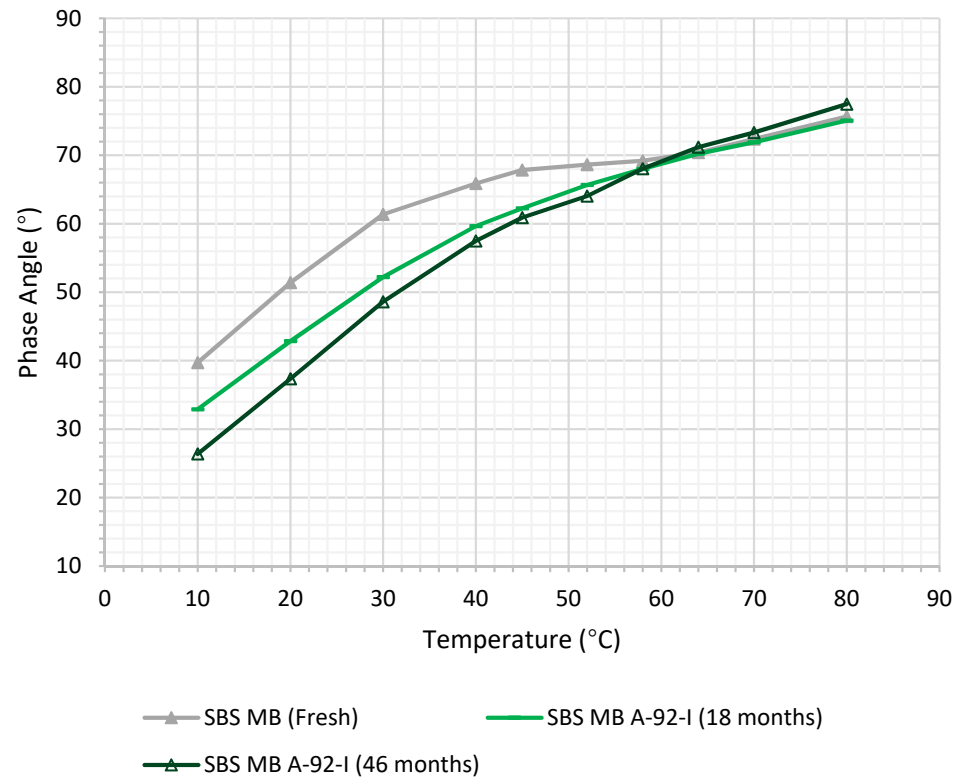
**Figure 19.** Isochrone curves at 5 Hz of the complex modulus of the CRMB used in the A-92-II at different service-life periods.



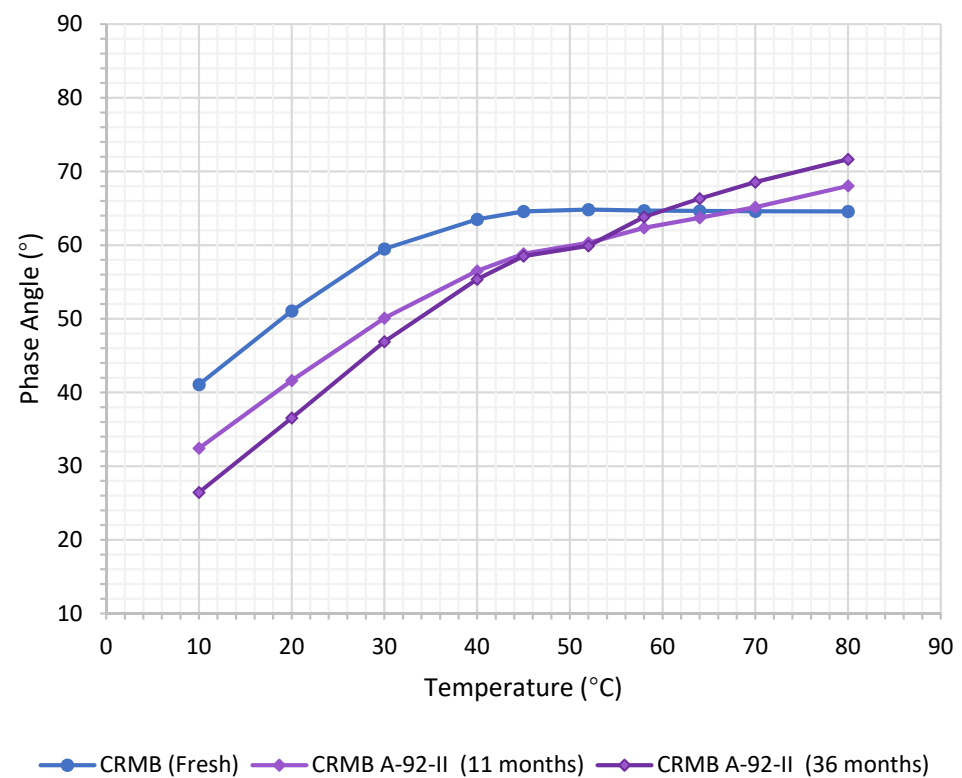
**Figure 20.** Isochrone curves at 5 Hz of the complex modulus of the SBSMB used in the A-92-II at different service-life periods.



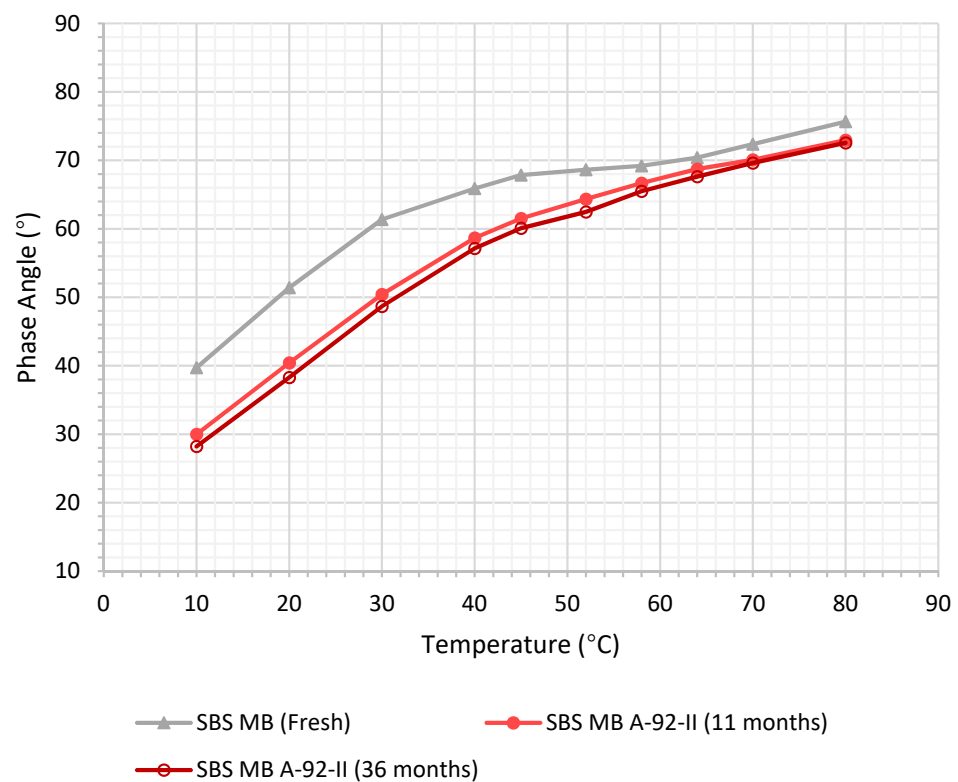
**Figure 21.** Isochrone curves at 5 Hz of the phase angle of the CRMB used in the A-92-I at different service-life periods.



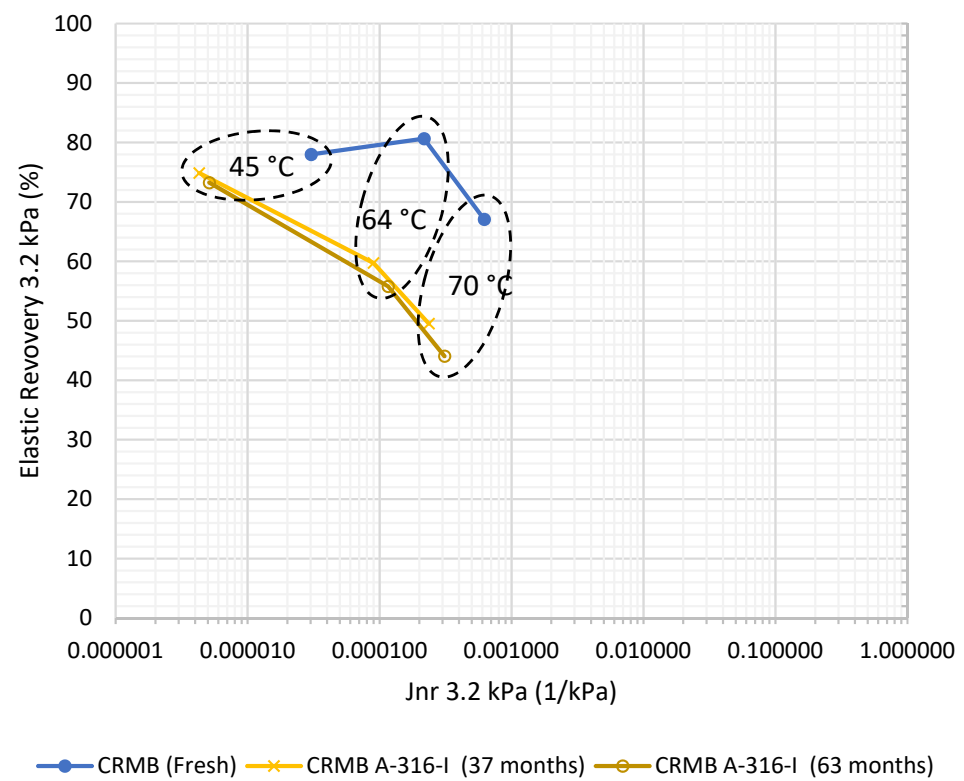
**Figure 22.** Isochrone curves at 5 Hz of the phase angle of the SBSMB used in the A-92-I at different service-life periods.



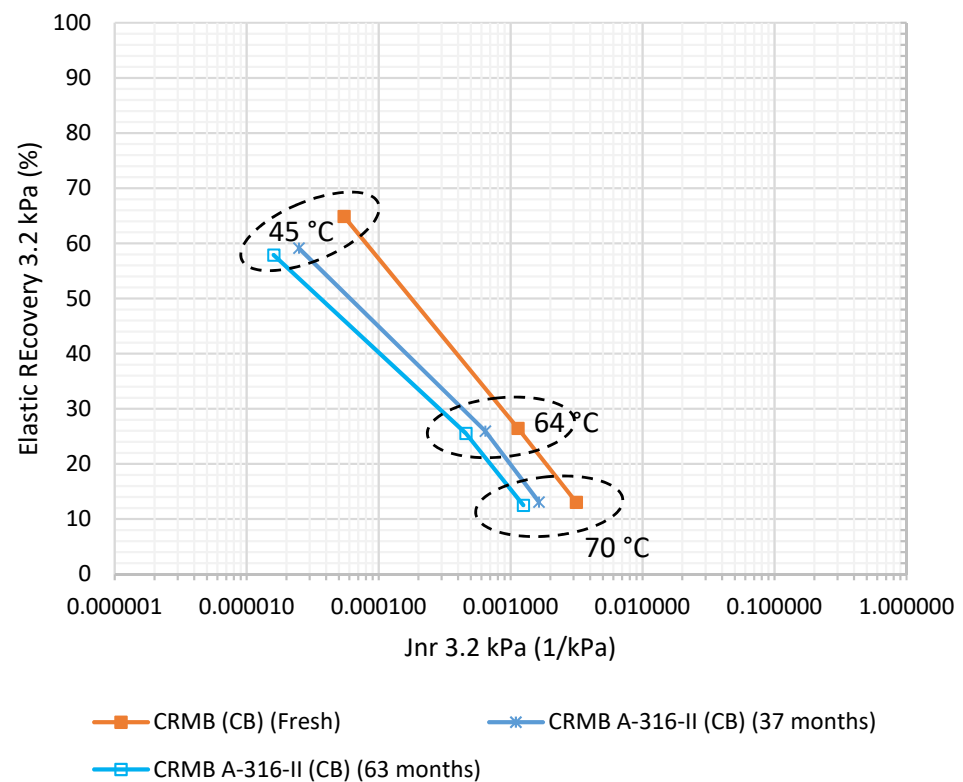
**Figure 23.** Isochrone curves at 5 Hz of the phase angle of the CRMB used in the A-92-II at different service-life periods.



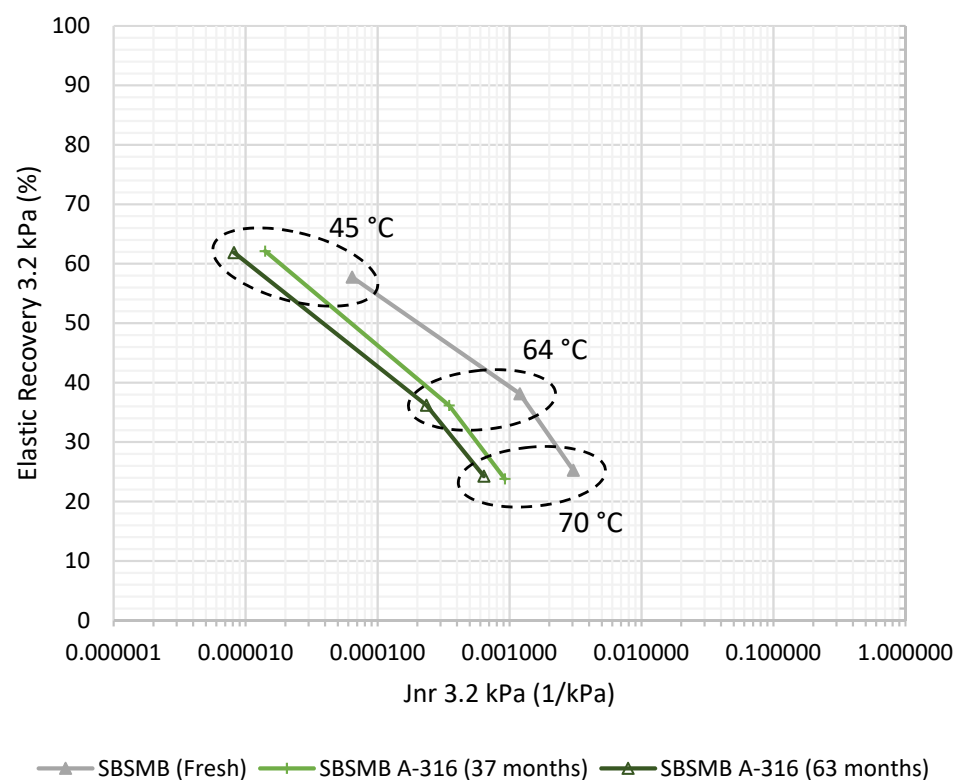
**Figure 24.** Isochrone curves at 5 Hz of the phase angle of the SBSMB used in the A-92-II at different service-life periods.



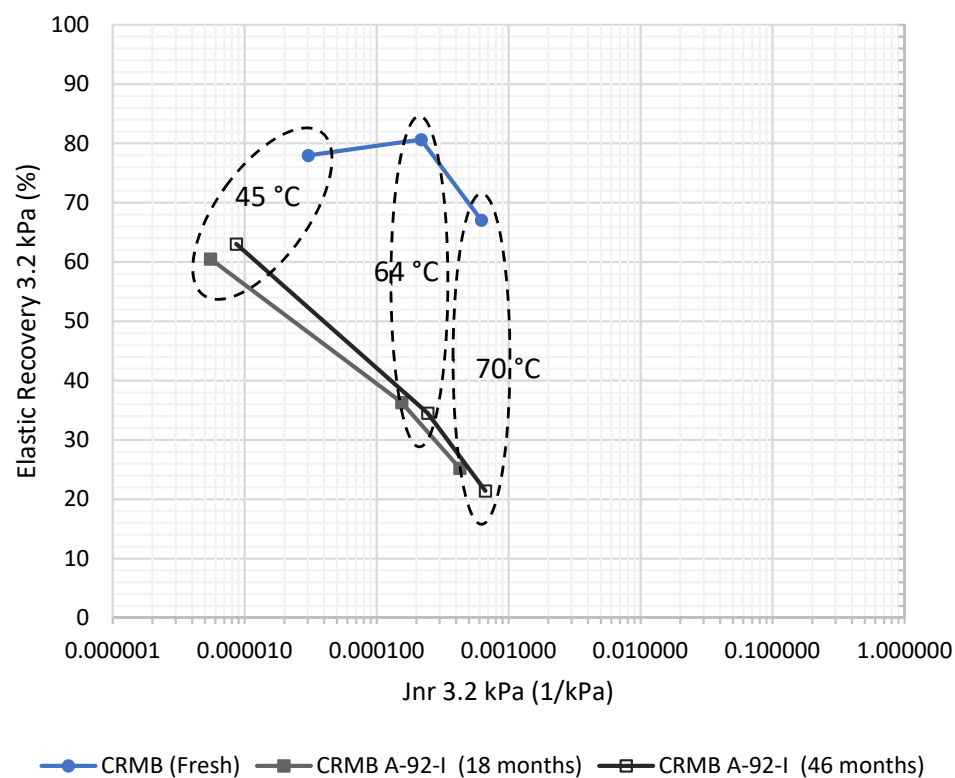
**Figure 25.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the CRMB used in the A-316-I at different service-life periods.



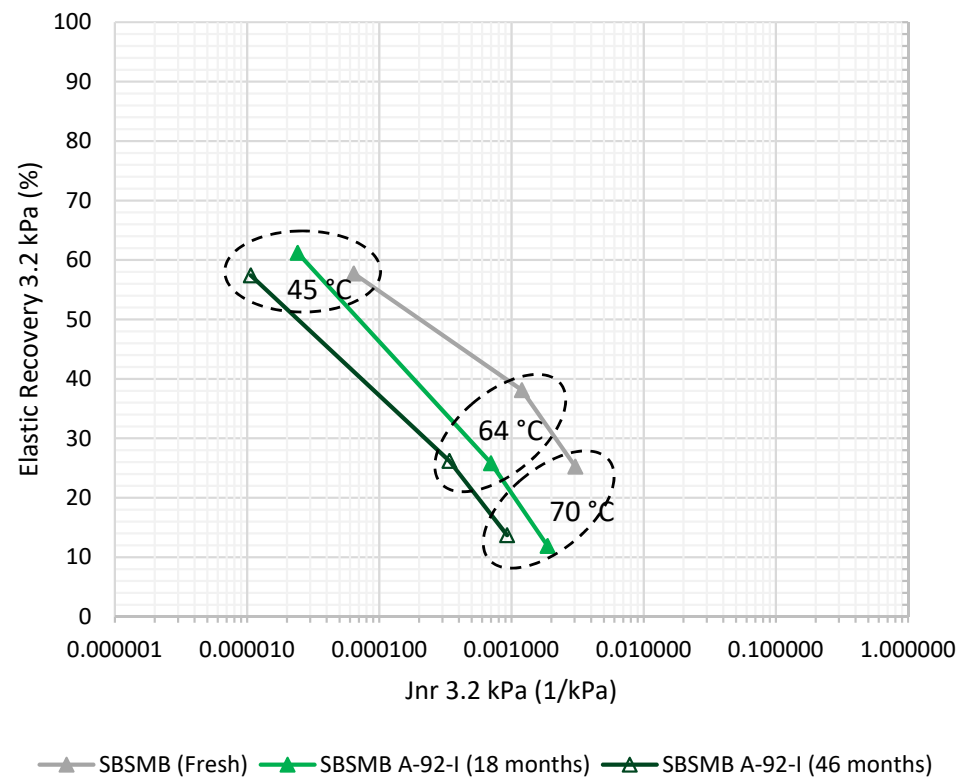
**Figure 26.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the CRMB (CB) used in the A-316-II at different service-life periods.



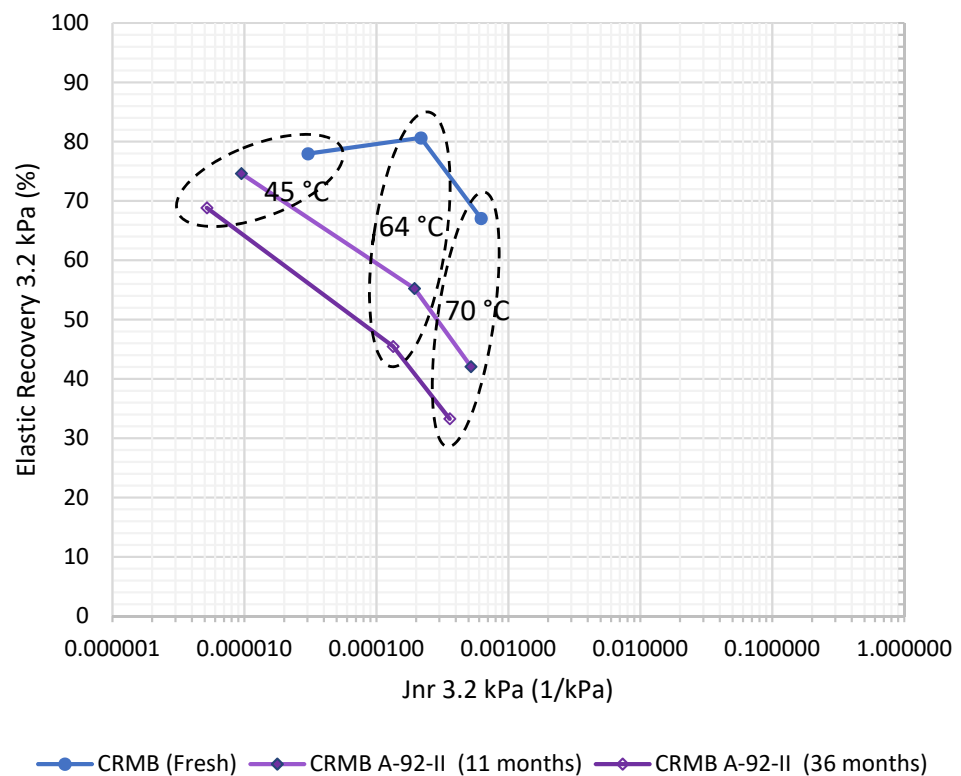
**Figure 27.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the SBSMB used in the A-316 at different service-life periods.



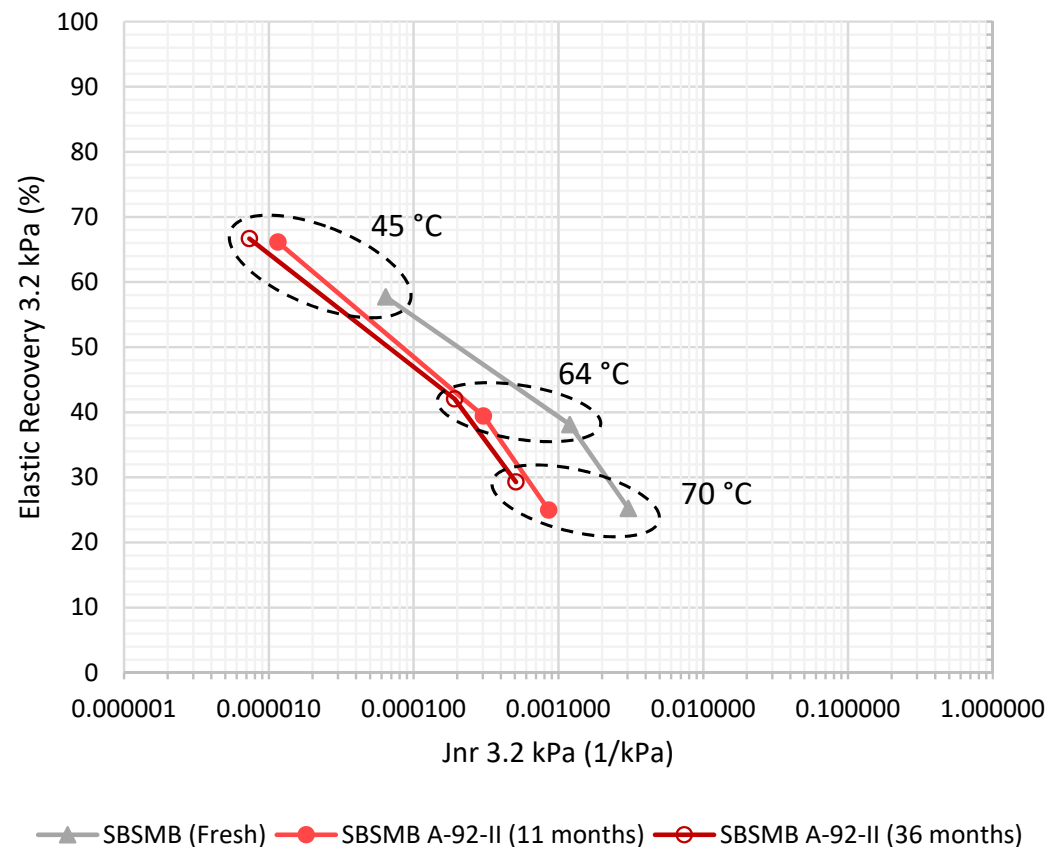
**Figure 28.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the CRMB used in the A-92-I at different service-life periods.



**Figure 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.



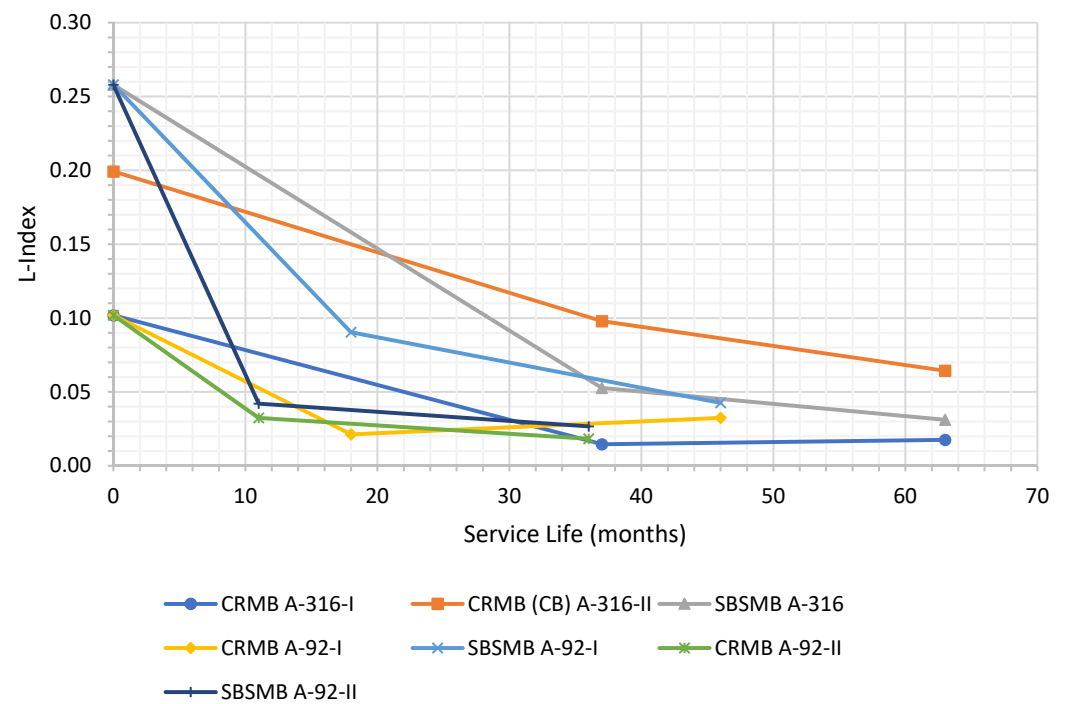
**Figure 30.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the CRMB used in the A-92-II at different service-life periods.



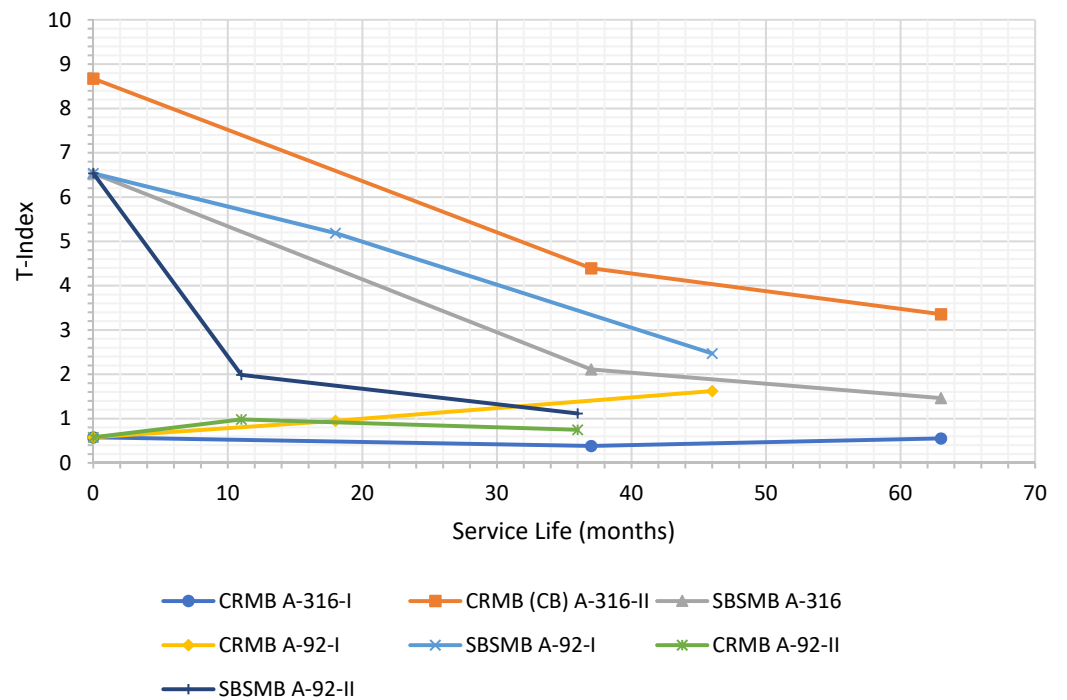
**Figure 31.** Non-recoverable creep (Jnr) and elastic recovery measured with the MSCRT on the SBSMB used in the A-92-II at different service-life periods.

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 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 33).

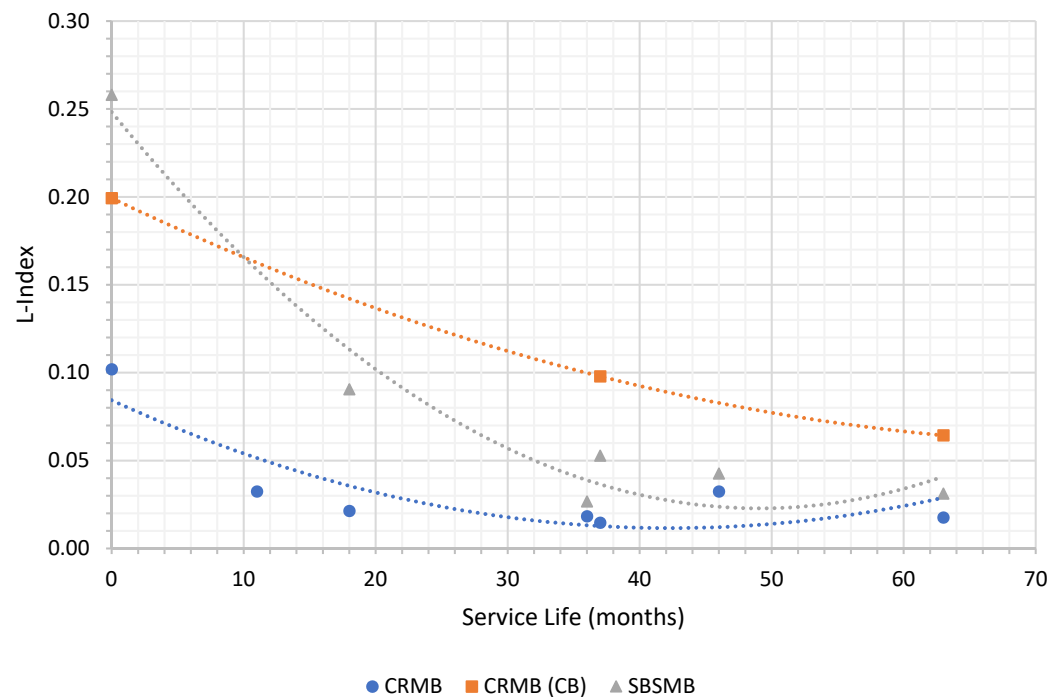
As a general conclusion, it can be stated that regardless of the scenario studied, the three binders evaluated were found to have similar evolutions of their rheological properties as a function of the service life. Figures 34 and 35 analyse the L-Index and T-Index of the binders studied overall, regardless 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.



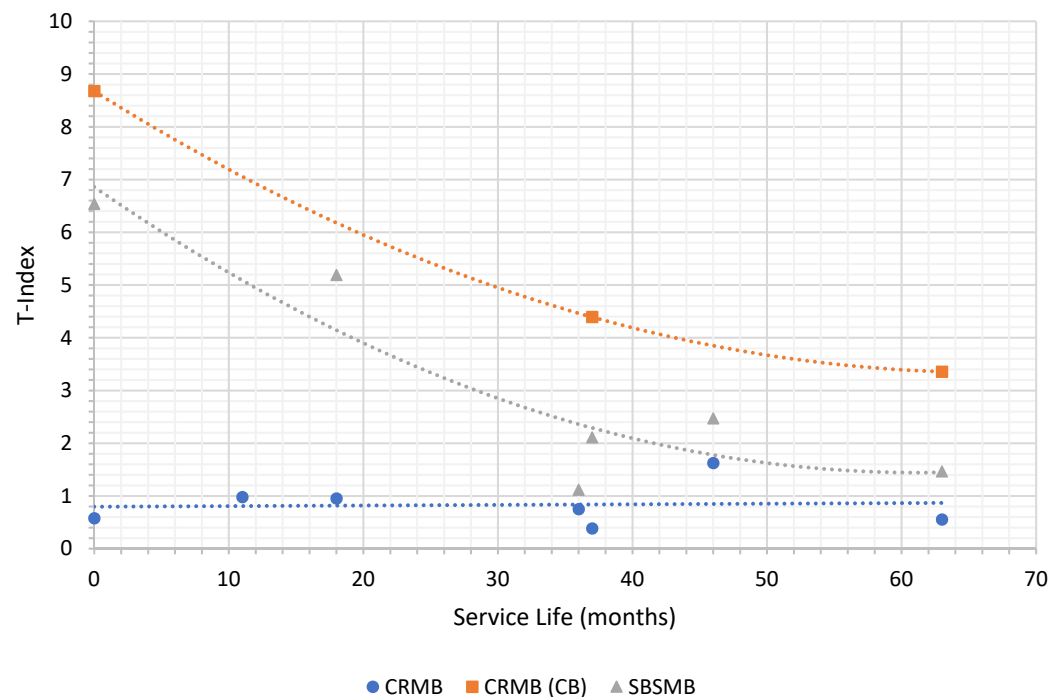
**Figure 32.** Evolution of L-Index as a function of the service life for the different asphalt binders and highway sections studied.



**Figure 33.** Evolution of the T-Index as a function of the service life for the different asphalt binders and highway sections studied.



**Figure 34.** Evolution of the L-Index as a function of the service life for the different asphalt binders studied.



**Figure 35.** Evolution of the T-Index as a function of the service life for the different asphalt binders studied.

#### 4. 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.

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